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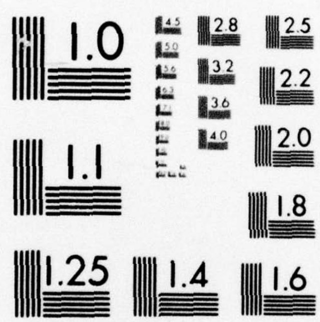

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This study revised and updated the appropriate sections of Military Handbook 217B, "Reliability Prediction of Electronic Equipment," pertaining to resistors, capacitors, and inductive devices. In addition to updating the existing sections in the Handbook, 15 part specifications were added. More than 335 billion part-hours of field operating data were collected and analyzed during the study effort. Significant revisions were made to base failure rates, environmental factors, and some quality factors. Other changes included the addition of a capacitance factor to the capacitor section.

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SUMMARY

This report comprises the results of a 14-month program conducted by Martin Marietta Aerospace to revise the resistor, capacitor, and inductive devices sections of MIL-HDBK-217B, "Reliability Prediction of Electronic Equipment." This report summarizes the data collected and the revisions to the Handbook failure rate models; however, the actual revision sheets to be inserted into the Handbook are provided separately and are not a part of this report.

More than 335 billion part hours of operating data were collected in nine different environmental applications. Table 1 summarizes the quantity of part hours collected for each part class. The data were obtained as a result of an extensive data collection program that extended to private contractors, Government facilities, and research institutions throughout the country. The collected data were grouped, analyzed, and statistically tested for homogeneity before being combined.

TABLE 1

Summary of Operating Data Collected by Part Class

Part Class	Part Hours ($x10^6$)
Resistors	243,613.572
Capacitors	87,192.848
Coils	3,059.197
Transformers	1,399.881
Total	335,265.498

The study encompassed a total of 57 part specifications, 15 of which are not presently in MIL-HDBK-217B. Significant changes were made to the base failure rates and environmental factors for many part types. Quality factors for established reliability parts were not changed because of an insufficient quantity of data at the higher levels; however, the Military Standard and lower grade factors were revised for some parts. The airborne environmental factors were expanded from two to four to delineate between subsonic and supersonic aircraft. An additional factor that varies as a function of rated capacitance was included in the fixed capacitor failure rate models. Also, an additional factor was included in the non-solid tantalum capacitor model which accounts for different construction techniques such as foil versus slug, hermetic and nonhermetic, and the relatively new all-tantalum style.

Most revisions to existing failure rate models did not follow definite trends. Several potentiometer base failure rates were reduced, particularly those for the non-wirewound RJ style. Paper and paper-plastic capacitor base failure rates were significantly increased. Transformer failure rates were increased while those for coils were decreased.

One relatively new part type for which a failure rate model was developed is resistor networks (MIL-R-83401). This model is considered to be an interim model until it can be further validated by field data.

PREFACE

This final report was prepared by the Orlando Division of Martin Marietta Aerospace for the Rome Air Development Center (RADC), Griffiss Air Force Base, New York, under Contract F30602-76-C-0398. The purpose of the contract was to revise and update MIL-HDBK-217B passive device sections that include resistors, capacitors, and inductive devices.

This report is submitted as the technical report input for CDRL Sequence Number A002 and covers the period from September 1976 to November 1977. The original termination date of the study was September 1977; but because of delays encountered in the acquisition of data required for the effort, the study completion date was extended to November 1977 at no additional cost to the Government. The RADC Project Engineer was Mr. Lester J. Gubbins (RBRS).

In addition to Messrs. Cottrell, Hierholzer, and Olson, other contributors to the acquisition and analysis of data were: Thomas Butler, Thomas Gagnier, Kurt Gonzenbach, George Guth, Edwin Kimball, Thomas Kirejczyk, William Maynard, Lynn Mercer, Sharon Molnar, Aaron Penkacik, Betty Thomas, Lynn Westling, Robert Whalen, and Thomas Young.

EVALUATION

This contractual effort is part of the broad RADC Reliability Program to provide reliability prediction procedures for military electronic equipment and systems. These prediction procedures are contained in MIL-HDBK-217B for which RADC is the preparing activity. The failure rate models developed in this study will replace the models for resistors, capacitors, and inductive devices that are presently in MIL-HDBK-217B.

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SECTION I

INTRODUCTION

This study consisted of revising and updating the appropriate sections in MIL-HDBK-217B pertaining to resistors, capacitors, and inductive devices (hereinafter called passive devices). Although the passive device models in MIL-HDBK-217B have undergone some minor changes from their predecessors, these models have not received a thorough review since the publication of Volume II of the Rome Air Development Center (RADC) Reliability Notebook. Passive devices continue to be used in significant quantities in new electronic equipment and their large populations can have a definite impact on total equipment reliability. Therefore, in September 1976, RADC awarded Martin Marietta Contract Number F30602-76-C-0398, entitled "Passive Device Failure Rate Models for MIL-HDBK-217B." The purpose of the contract was to revise and update sections 2.5, 2.6, and 2.7 of MIL-HDBK-217B, to evaluate existing models for necessary changes, and to develop new models for passive devices not presently included in MIL-HDBK-217B. This report details the results of that contractual effort.

SECTION II

DATA ANALYSIS

2.1 Statistical Methods, Assumptions, and Ground Rules

Operational data on passive components were collected, analyzed, and summarized by component type, use environment, and quality grade. The following sections describe the basic ground rules and assumptions used in this analysis and define the statistical tests used in combining the data. The method used for calculating failure rates at a given confidence level is included. Numerical examples are given for the statistical tests and the calculation of failure rates.

2.1.1 Calculation of Failure Rates

All failure rates are calculated at the upper single-sided 60 percent confidence level. Prior to calculating the confidence levels, it had to be determined whether the component data were time or failure truncated. Since no known instances of failure truncated information were reported, received, or documented, it was assumed that the data were time truncated. The upper 60 percent confidence level failure rate can be calculated by using the component part hours and the Chi square (χ^2) value at 2r + 2 degrees of freedom at the 40 percent level of significance point. If the data had been failure truncated, the value would be obtained at 2r degrees of freedom. The following general equation obtained from Reference 1 is used for calculating the failure rate:

$$\frac{\chi^2(\alpha,\ 2r + 2)}{2T} = \text{Upper single-sided confidence level}$$

Where:

r = Number of failures and determines the degree of freedom coordinate used in determining χ^2

2r + 2 = Total number of degrees of freedom

α = Acceptable risk of error (40 percent in this study)

$1-\alpha$ = Confidence level (60 percent in this study)

T = Total number of component part hours.

1. ARINC Research Corporation, "Reliability Engineering," page 173, Prentice-Hall Inc., Engelwood Cliffs, New Jersey, 1964.

As an example, two failures during 20.722×10^6 part hours of airborne operation were used in calculating the failure rate at the upper single-sided 60 percent confidence level on power wirewound resistors. Reference 2 was used as the source for the χ^2 value. The results are as follows:

$$\text{Failure rate (60 percent confidence)} = \frac{\chi^2\ (0.40,\ 6)}{2T} = \frac{6.21}{41.444 \times 10^6}$$

Failure rate (60 percent confidence) = 0.150 failures/10^6 part hours.

Since the statistical tables used are limited to χ^2 values up to 100 degrees of freedom, it was necessary to calculate an estimate of the χ^2 percentile points wherever more than 49 failures were observed in the data. In accordance with Reference 2, χ^2 confidence level values are approximated by:

$$\chi_p^2 \approx 1/2\ (Z_p + \sqrt{2f - 1})^2$$

Where:

χ_p^2 = Approximated χ^2 value

f = Total number of degrees of freedom

Z_p = 0.25335 and is the value of the standard normal variable at the 60 percent significance level.

Using actual data from power wirewound resistors, which had 437 failures in $5{,}312.68 \times 10^6$ part hours of fixed ground operation, the failure rate for the upper single-sided 60 percent confidence level is calculated as follows:

$$\text{Failure rate (60 percent confidence)} = \frac{1/2(0.25335 + \sqrt{2(876)-1})^2}{2(5{,}312.68 \times 10^6)}$$

Failure rate (60 percent confidence) = 0.083 failures/10^6 part hours.

2.1.2 Test of Homogeneity of Data

As billions of part-hours of data are collected from many different sources, the analyst is faced with the task of determining how the data should be combined. Homogeneity of component/part type populations must be maintained to prevent the introduction of bias and loss of precision in component failure rates. Therefore, all line items of failure rate data were carefully studied and evaluated, and then reordered and categorized on the basis of component type, component subgroup type, quality grade, and environmental application.

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2. Hald, A., "Statistical Tables and Formulas," Table V, pages 41-43, John Wiley and Sons, Inc., New York, 1952.

Before combining the data, a statistical test for homogeneity was required. The Dixon Criterion test was chosen to statistically detect and identify those data entry failure rates that might significantly deviate from the family of failure rate entries under analysis. The ground rules and statistical assumptions used for Dixon Criterion testing are as follows:

1 Failure rate observations derived from each line entry come from a single normal population.

2 Population mean and standard deviation of the failure rate observations are unknown. The data sample, consisting of the failure rate line entries, is the only source of information.

3 The probability of risk (α) for rejecting an observation that truly belongs in the group is 10 percent. Line items significantly different at either end of a 90 percent two-sided confidence interval are culled from the sample before a final combined failure rate estimate is calculated. (See section 2.1-1 for a discussion of the method used for calculating confidence intervals.)

4 A minimum of three line entries of failure rate data is necessary in testing the homogeneity of the samples.

As an example, Table 2 contains five ordered line items of failure data received on metal film resistors and the formulas for identifying outliers at the upper and lower ends for a sample size of five items. The formula for testing at the high end for a sample size of four is also included.

TABLE 2

Combination of Failure Data Line Entries

Metal Film Resistors

Failure Rate (Failures/10^6 Part-Hours)	Part-Hours ($\times 10^6$)	Failures
X_1 = 0.00024	8374.005	2
X_2 = 0.00065	1529.973	1
X_3 = 0.00350	288.586	1
X_4 = 0.00480	4538.441	22
X_5 = 0.25000	31.860	8

For a sample size of five and if the low end is suspect,

$$\text{reject } X_1 \text{ if } \frac{X_2 - X_1}{X_5 - X_1} \geq 0.642$$

For a sample size of five and the high end is suspect,

$$\text{reject } X_5 \text{ if } \frac{X_5 - X_4}{X_5 - X_1} \geq 0.642$$

For a sample size of four and the high end is suspect,

$$\text{reject } X_4 \text{ if } \frac{X_4 - X_3}{X_4 - X_1} \geq 0.765$$

To test acceptability of sample X_1 at the low end, the applicable failure rates in failures 10^6 part-hours are substituted into the corresponding formula and the result obtained is:

$$\frac{X_2 - X_1}{X_5 - X_1} = \frac{0.00065 - 0.00024}{0.25 - 0.00024} = 0.002.$$

This value is less than 0.642; therefore, for a sample size of five, the lowest ordered failure rate is within the acceptable boundary. To test acceptability of sample entry X_5 at the high end, again the applicable values are substituted into the corresponding formula for a sample size of five and the result obtained is:

$$\frac{X_5 - X_4}{X_5 - X_1} = \frac{0.250 - 0.0048}{0.250 - 0.00024} = 0.982.$$

This value is greater than 0.642. Therefore, the failure rate, 0.250, and its associated part-hours and failures must be rejected and would not be combined in the final failure rate estimate.

The test is rerun for a sample of four entries. Again, sample entry X_1 at the low end is found not to be rejected. At the high end, the result obtained is:

$$\frac{X_4 - X_3}{X_4 - X_1} = \frac{0.0048 - 0.0035}{0.0048 - 0.00024} = 0.285$$

which is less than 0.765. This time all data are accepted. Thus, an iterative testing process using the Dixon Criterion is continued until both the low end and high end values are accepted.

The data and tables used for determining formulas and statistics to be applied for various sample sizes were obtained from Reference 3.

2.2 General Analysis Procedure

A general method for analyzing the collected data was utilized to determine new base failure rates and the effects of different environments and quality grades. The method developed normalizes the effects of actual temperature and stress realized by the parts on which data were collected and compares the results to the existing base failure rates and modifying factors in MIL-HDBK-217B. Where significant differences occurred, revised model parameter values were derived. However, throughout the analysis, engineering logic was used in conjunction with analytical results in developing the model parameters.

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3. Natrella, Mary G., "Experimental Statistics," pages 17-1 through 17-3, National Bureau of Standards Handbook 91, August 1963.

Additional analyses were performed to fill in gaps in the collected data with the primary purpose being to ensure consistency between a given model's quantitative factors that were changed as a result of the collected data and the remaining factors that could not be verified or changed because of lack of data.

2.2.1 Preparing Raw Data for Analysis

The general analysis method is illustrated by the procedure used to analyze the data collected on MIL-R-94, Variable Composition Resistors (RV style). First, as shown in Table 3, the data were summarized by environment and quality grade. The observed failure rate was then calculated at the 60 percent one-sided upper confidence level. It was not found practical to summarize the data to more detailed levels, such as temperature and stress, because the data then became so sparse in most categories that realistic failure rates could not be calculated. In most cases temperature was found to remain in a reasonably narrow range (10 to 15°C) within a given use environment. For example, most fixed ground data were generated at an ambient temperature range of 30 to 40°C.

Second, the data were analyzed to determine predicted failure rates using MIL-HDBK-217B for each category upon which observed data exist. Failure rates, for variable composition resistors were summarized in the format shown in Table 4. Temperature and stress information obtained from the data sources was used in determining these failure rates. If there were several temperatures/stresses involved for a given category, an average was used. However, this average was weighted heavily towards the source or sources representing the largest quantity of data. In a few cases the temperatures/stresses were not available from the data source and had to be estimated.

2.2.2 Base Failure Rate Analysis

Data were now ready to be analyzed for deviations from the existing MIL-HDBK-217B failure rate models. The procedure shown in Table 5 was used to determine differences in the observed versus predicted failure rates for specific environments and quality grades. Data in this table indicate that the basic failure rate in MIL-HDBK-217B composition potentiometers (RV style) is too high since all three environments have a high predicted-to-observed ratio. The smallest ratio, 5.4, was used to reduce the base failure rate, λ_b, in MIL-HDBK-217B for RV resistors. If the handbook base failure rate is reduced by a factor of 5.4, the predicted value is equal to the observed value for the ground mobile environment. This fixes the ground mobile environment as a standard with which all other environments can be compared.

2.2.3 Environmental Factor Analysis

Before environmental comparisons can be made, failure rate variations caused by other factors such as temperature and stress should be eliminated. For example, the ideal method for differentiating the effects between fixed ground and airborne environments is to use identical equipments in each situation with all other variables fixed except for the environment. Unfortunately,

TABLE 3

Example of Format Used to Summarize Collected Data

Part Type: Variable Composition Resistor, MIL-R-94(RV)

Environment	Quality Grade														
	MIL			M			P			R			S		
	Pt-Hrs ($x10^6$)	Fail	$\lambda^* x10^{-6}$	Pt-Hrs ($x10^6$)	Fail	$\lambda^* x10^{-6}$	Pt-Hrs ($x10^6$)	Fail	$\lambda^* x10^{-6}$	Pt-Hrs ($x10^6$)	Fail	$\lambda^* x10^{-6}$	Pt-Hrs ($x10^6$)	Fail	$\lambda^* x10^{-6}$
A_I	0.0050	0	--												
G_F	56.5040	12	0.2406												
G_M	2.0353	3	2.051												
N_S	7.4820	2	0.415												
G_B	0.7550	0	1.212												

*Failure rate is calculated as 60 percent one-sided upper confidence level.

TABLE 4

Example of Format Used to Predict Failure Rates from MIL-HDBK-217B for Observed Operating Conditions

Part Type: Variable Composition Resistor, MIL-R-94(RV)

	Quality Grade														
	MIL			M			P			R			S		
Environment	λ*	Stress	Temp °C	λ*	Stress	Temp °C	λ*	Stress	Temp °C	λ*	Stress	Temp °C	λ*	Stress	Temp °C
A_I	12.2500	0.3	40												
G_F	1.9750	0.1	35												
G_M	11.1250	0.3	30												
N_S	11.1250	0.3	30												
G_B	0.2375	0.3	37												

*Failure rate calculated from MIL-HDBK-217B

TABLE 5

Observed Versus Predicted Failure Rates for RV Potentiometers

Environment	Predicted λ / Observed λ	λ Ratio
Ground fixed (G_F)	$\frac{1.975}{0.241}$	8.2
Ground mobile (G_M)	$\frac{11.125}{2.051}$	5.4
Naval sheltered (N_S)	$\frac{11.125}{0.415}$	26.8

the data collected in different environments usually varied by equipment type as well as temperature and stress. Therefore a method had to be developed to normalize the observed failure rates to one set of temperature and stress values, leaving environment as the primary variable represented by the differences in these adjusted failure rates.

The procedure used to normalize the observed failure rates is illustrated in Table 6. In this method the base failure rates from all environments are normalized to the temperature and stress conditions of one selected environment. In this example, the selected environment is ground mobile since that was the standard chosen during the base failure rate comparisons. The only logical way to normalize the failure rates was to use the temperature versus stress base failure rate tables in MIL-HDBK-217B. The relative variations between temperature and stress given in these tables were assumed to be correct - an assumption which could not be verified by a study program of this scope.

TABLE 6

Normalization of RV Resistor Failure Rates

Environment	Observed Temperature (^oC)	Observed Stress	MIL-HDBK-217B λ_b	λ_b Normalized to G_M Environ
Ground fixed (G_F)	35	0.1	0.079	$\frac{0.079}{0.089} = 0.89$
Ground mobile (G_M)	30	0.3	0.089	$\frac{0.089}{0.089} = 1$
Naval sheltered (N_S)	30	0.3	0.089	$\frac{0.089}{0.089} = 1$

The normalization factors obtained by the procedure outlined in Table 6 were applied to the observed failure rates of each respective environment to obtain failure rates under equivalent temperature and stress conditions to the ground mobile values. For example:

Ground fixed environment:

$$\lambda_{Norm} = \frac{\text{Observed } \lambda}{\text{Normalization factor}} = \frac{0.241}{0.890} = 0.271 \text{ failure}/10^6 \text{ hours}$$

Naval sheltered environment:

$$\lambda_{Norm} = \frac{\text{Observed } \lambda}{\text{Normalization factor}} = \frac{0.415}{1} = 0.415 \text{ failure}/10^6 \text{ hours.}$$

Thus, the observed ground fixed failure rate is adjusted by the normalization factor of 0.89 to obtain the equivalent failure rate at 30°C and 0.30 stress ratio. This yields a slightly higher failure rate than that originally observed. Since the naval sheltered temperature and stress were the same as that for ground mobile data, this failure rate does not change.

Finally, to determine the relative effects of different environments, the ratio was obtained between each adjusted observed failure rate and the selected standard failure rate (ground mobile in our example):

$$\frac{\lambda_{GF}}{\lambda_{GM}} = \frac{0.271}{2.051} = 0.132$$

$$\frac{\lambda_{NS}}{\lambda_{GM}} = \frac{0.415}{2.051} = 0.202.$$

The new environmental factors for each environment can now be obtained by multiplying the respective ratio value by the environmental factor given in MIL-HDBK-217B for the selected standard environment. In this example the environment used as a standard was ground mobile which has an environmental factor of 50 in MIL-HDBK-217B. Therefore, the new environmental factors for RV potentiometers are:

Ground fixed = 50 (0.132) = 6.6

Naval sheltered = 50 (0.202) = 10

Ground mobile = 50 (1) = 50.

2.2.4 Additional Analyses

The data collected on RV potentiometers allowed a comparison of the relative differences among three environments: ground fixed (G_F), ground mobile

(G_M), and naval sheltered (N_S). However, two environments, space flight (S_F) and ground benign (G_B), are grouped together as a baseline with an environmental factor value of 1.0 for nearly all parts. The revised G_F factor would indicate a variation of 6.6 to 1 between G_F and S_F/G_B environments which appears to be high. In MIL-HDBK-217B this variation is 10 to 1. Part characteristics were researched and part specialists consulted, but no justification was found for this large variation. The G_F environment could allow more temperature and humidity variation and some vibration, but these effects are not usually excessive in the G_F environment. Therefore, it was decided that a conservative variation between G_F and S_F/G_B would be 3 to 1.

If the G_F environmental factor is reduced from 6.6 to 3, then the factors for the G_M and N_S environments should also be proportionally reduced. However, to maintain the same overall observed failure rate, the base failure rate must be increased to offset the environmental factor reduction. The initial recommendation given in section 3.2.3 was to divide the base failure rates in MIL-HDBK-217B for RV potentiometers by 5.4. This value would now be changed to 2.4 to maintain the same overall failure rate. This is equivalent to multiplying the base failure rate by 0.4. Therefore, the final recommendations for changing the RV potentiometer model as a result of data collected on this part are given in Table 7.

TABLE 7

Recommended Changes for RV Resistor
Based on RV Data Analysis

Model Parameter	Recommended Change to MIL-HDBK-217B
Base failure rate (λ_b)	Decrease by factor of 0.4
Environmental factors (Π_E):	
Ground benign (G_B)	Remains 1.0
Ground fixed (G_F)	Change from 10 to 3
Naval sheltered (N_S)	Change from 50 to 4.5
Ground mobile (G_M)	Change from 50 to 23

In situations where gaps in the collected data existed, some environmental factors were derived as a result of engineering studies and group trend analyses. An example of a group trend analysis is the N_S environmental factor where, almost without exception, the observed failure rates in this environment were significantly less than those predicted by MIL-HDBK-217B. Therefore, based upon this lower trend, the N_S factor was adjusted lower on several part types on which no data were collected in this environment.

The analysis techniques discussed in this section were generally applied to all data collected on resistors, capacitors, and magnetic devices. Some variations were used depending upon the form of the data. If less than three environments were represented for a given part type, these techniques were generally not used. Instead, changes were recommended, as appropriate, to the particular environmental factors represented by the data. A change in the base failure rate of a part type was considered primarily if data on three or more environments were available. Quality levels were evaluated using ratio methods similar to those discussed in this section. However, because of the large quantities of data required at the higher quality levels to obtain realistic failure rates, the quality factors in MIL-HDBK-217B could not be verified for most part types.

2.3 Summary of Data Collected

More than 335 billion part hours of data were collected on passive components during this study program. No components were tested to obtain data, but rather an extensive data survey and collection effort was undertaken to locate and obtain necessary data. Data were obtained from a comprehensive literature search and from direct contact with potential sources of data.

A total of 560 contractors, institutions, and Government agencies were sent a data survey letter which explained the purpose of the study program and requested a response to a short questionnaire concerning availability of pertinent data. Approximately 260 responses were received. Favorable responses were followed up by telephone calls and, where deemed necessary, personal visits. Visits were made to a total of 47 data sources which resulted in the accumulation of the majority of the data collected.

The collected data are summarized in Appendix A, Tables A-1, A-2, A-3, and A-4, for resistors, capacitors, transformers, and inductors, respectively. All failure rates in these tables are given at the 60 percent single-sided upper confidence level. Failure rates were not calculated when less than 0.5 million part hours were collected. The environmental abbreviations are the same as those in MIL-HDBK-217B except for airborne where an additional letter designation has been added. The subscript "T" on the airborne abbreviations designates data generated in subsonic type aircraft such as transport and cargo planes while the subscript "F" refers to supersonic aircraft such as fighters. The quality levels given in the tables are usually either Military Standard or the appropriate Established Reliability (ER) levels. However, two other notations are also given: "lower" refers to parts less than Military Standard quality such as commercial, and "higher" refers to Military Standard grade parts that have been subjected to extra testing.

Component failure is defined as the inability of the component to properly perform its intended function, resulting in its being repaired or replaced. Whenever detailed failure information was available, all secondary failures, premature removals, procedural, and personnel errors were censored.

Since most data obtained listed only the quantity of failures and experience with no elaboration of failure modes and mechanisms, much of the data are dependent upon each source's ability to properly categorize its equipment

failures. As a result of direct contact with most of the sources, however, it is felt that the majority of data contributed to this study was properly screened by the contributors. As an additional check, a statistical outlier test was performed on the data, and any data which deviated significantly from the majority were eliminated. Therefore a high degree of confidence has been developed which warrants the practical application of these data.

A listing of the data sources contributing to the study program is given in Appendix B.

SECTION III

ANALYSIS RESULTS

This section presents the results of the analyses of the data collected during the program effort. These results are expressed in terms of recommended revisions to the existing data in MIL-HDBK-217B. The complete quantitative models and factors will be prepared on sheets suitable for insertion in MIL-HDBK-217B and submitted as a separate document. The primary revisions are with the base failure rates and environmental factors. Fewer changes have been recommended for quality factors because of a lack of comparative data in most quality levels. However, the upper quality level category was eliminated from all non-ER specifications because of the lack of a clear definition as to when a part should be included in it. Other revisions, including recommended additions and deletions, are discussed in the appropriate subsections.

3.1 Resistor Analysis Results

During the study program, the failure rate models for the 22 resistor specifications presently in MIL-HDBK-217B were analyzed and models for four additional specifications were developed. A complete listing of the 26 specifications covered in this study is given in Table 8, while the additional specifications are shown separately in Table 9. Although some of these specifications are inactive, they have been retained in the Handbook because of the large number of equipments still in field use which contain these parts. The recommended revisions to the base failure rates and environmental factors are depicted in Table 10 along with the respective values presently in MIL-HDBK-217B. The base failure rates are for a temperature of 30°C and an electrical stress of 0.30.

The specifications in Table 10 are grouped in pairs where both the Military Standard and Established Reliability versions are available. The base failure rates are the same for each pair since the quality factors are used to differentiate between different levels of reliability within a given part type. The only resistor specification for which the quality factor was changed is MIL-R-10509. The factor for this part type was changed to 2.0 from 1.0 in the present Handbook. The airborne environments have been expanded to distinguish between supersonic and other types of aircraft. In Table 10 it is assumed that the environmental factors in MIL-HDBK-217B represent the nonsupersonic or subsonic environment.

Two specifications are not included in Table 10 because their models are not presented in the same general format as those of the other resistors. These two specifications are MIL-R-83401, Resistor Networks, and MIL-T-23648, Thermistors. The resistor network model is new as this specification is not covered in MIL-HDBK-217B. These two models are presented in subsections 3.1.3 and 3.1.4.

An additional formula has been developed for calculating a potentiometer stress ratio when used in a rheostat application. The formula given in MIL-HDBK-217B is applicable only to the conventional 3-terminal application.

TABLE 8

Resistor Specifications to be Included in Revision to MIL-HDBK-217B

Part Specification	Style	Description*
Fixed Resistors		
MIL-R-11	RC	Composition
MIL-R-26	RW	Wirewound, Power
MIL-R-93	RB	Wirewound, Accurate
MIL-R-10509	RN	Film, High Stability
MIL-R-11804	RD	Film, Power
MIL-R-18546	RE	Wirewound, Power, Chassis Mounted
MIL-R-22684	RL	Film, Insulated
MIL-T-23648	RTH	Thermistor
MIL-R-39005	RBR	Wirewound, Accurate, ER
MIL-R-39007	RWR	Wirewound, Power, ER
MIL-R-39008	RCR	Composition, ER
MIL-R-39009	RER	Wirewound, Power, Chassis Mounted, ER
MIL-R-39017	RLR	Film, Insulated, ER
MIL-R-55182	RNR	Film, ER
MIL-R-83401	RZ	Resistor Network, Film
Variable Resistors		
MIL-R-19	RA	Wirewound, Low Operating Temperature
MIL-R-22	RP	Wirewound, Power
MIL-R-94	RV	Composition
MIL-R-12934	RR	Wirewound, Precision
MIL-R-22097	RJ	Metal, Cermet, or Carbon Film; Lead Screw Actuated
MIL-R-23285	RVC	Film
MIL-R-27208	RT	Wirewound, Lead Screw Actuated
MIL-R-39002	RK	Wirewound, Semi-Precision
MIL-R-39015	RTR	Wirewound, Lead Screw Actuated, ER
MIL-R-39023	RQ	Nonwirewound, Precision
MIL-R-39035	RJR	Metal, Cermet, or Carbon Film; Lead Screw Actuated; ER

*ER refers to established reliability.

TABLE 9

Resistor Specifications to be Added to MIL-HDBK-217

Specification	Style	Description
MIL-R-23285	RVC	Variable, Film
MIL-R-39023	RQ	Variable, Nonwirewound, Precision
MIL-R-39035	RJR	Variable; Metal, Cermet, or Carbon Film; Lead Screw Actuated; ER
MIL-R-83401	RZ	Resistor Networks, Fixed, Film

TABLE 10

Comparison of Revised Resistor Base Failure Rates and Environmental Factors with MIL-HDBK-217B Values

Part Type		Base Failure Rate (λ_b)		Environmental Factors																			
				G_B/S_F		G_F		A_{I_T}		A_{I_F}		N_S		G_M		N_U		A_{U_T}		A_{U_F}		M_L	
Specification	Style	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev
Variable																							
MIL-R-27208 MIL-R-39015	RT RTR	0.013	0.013	1	1	3	2	6	5	-	10	7	4	8	8	10	10	12	12	-	24	60	60
MIL-R-22097	RJ	0.557	0.025	1	1	3	3	6	5	-	10	8	4	10	10	12.5	12.5	15	15	-	30	80	80
MIL-R-39035	RJR	*	0.025	*	1	*	3	*	5	-	10	*	4	*	10	*	12.5	*	15	-	30	*	80
MIL-R-39023	RQ	*	0.032	*	1	*	3	*	5	-	10	*	4	*	10	*	12.5	*	15	-	30	*	80
MIL-R-23285	RVC	*	0.035	*	1	*	3	*	5	-	10	*	4	*	10	*	12.5	*	15	-	30	*	80
MIL-R-94	RV	0.089	0.036	1	1	10	3	50	6	-	12	50	4.5	50	23	55	25	60	27	-	54	100	100
MIL-R-19	RA	0.077	0.086	1	1	6	2	15	5	-	12	18	4	20	20	N/A		N/A		N/A		N/A	
MIL-R-39002	RK	0.077	0.086	1	1	6	2	15	5	-	10	18	4	20	20	N/A		N/A		N/A		N/A	
MIL-R-22	RP	0.091	0.091	1	1	6	2	15	5	-	10	17.5	4	20	20	N/A		N/A		N/A		N/A	
MIL-R-12934	RR	0.140	0.140	1	1	5	2	10	5	-	10	10	4	10	10	12	12	15	15	-	30	120	120
Fixed																							
MIL-R-11 MIL-R-39008	RC RCR	0.0003	0.0003	1	1	2	3	4	4	-	8	5	3	7	5	7.5	7.5	8	8	-	16	15	15
MIL-R-22684 MIL-R-39017	RL RLR	0.0018	0.0009	1	1	5	2	6.5	4	-	8	8	2	12	4	14	11	15	12	-	24	35	18
MIL-R-10509** MIL-R-55182	RN RNR	0.002	0.001	1	1	2.5	2	5	4	-	8	7.5	2	10	4	11	11	12	12	-	24	18	18
MIL-R-93 MIL-R-39005	RB RBR	0.004	0.004	1	1	6	2	15	6	-	12	18	2	20	8	23	15	30	20	-	40	70	40
MIL-R-18546 MIL-R-39009	RE RER	0.009	0.0045	1	1	3	2	6	4	-	8	7	2	10	5	11	11	12	12	-	24	30	30
MIL-R-26 MIL-R-39007	RW RWR	0.005	0.008	1	1	3	2	6	4	-	8	7	2	10	5	11	11	12	12	-	24	30	30
MIL-R-11804	RD	0.157	0.010	1	1	5	2	6.5	6	-	12	7.5	2	12	6	13.5	13.5	15	15	-	30	35	35

*Specification not in MIL-HDBK-217B.
**Quality factor changed from 1.0 to 2.0 (not included in this table).
NOTE: Base failure rates are calculated at 30°C and 0.30 electrical stress.

3.1.1 Base Failure Rates

A comparison of the recommended revision for each resistor base failure rate λ_b, to the existing failure rates in MIL-HDBK-217B has been given in Table 10. The revisions are based upon the analysis of the collected field operating data and, where insufficient data were available, upon ranking methodology.

Table 11 gives the quantitative change to be applied to the base failure rates in MIL-HDBK-217B in order to derive the revised rates. Also given in the table is the criteria used for changing the existing failure rate. Where ranking was the criteria used, this process was performed after all changes resulting from data analyses were determined. The ranking process consisted of an engineering evaluation of the part characteristics, both mechanical and electrical, compared with the parts for which data were available.

The largest change in base failure rate was with MIL-R-22097, Variable Non-Wirewound Resistor, which was decreased by a factor of 22. This change was based on data analyzed and was not surprising since the existing failure rate for this part type was not realistic when compared to those of other potentiometers. For example, Table 10 shows that the MIL-R-22097 base failure rate in MIL-HDBK-217B is about 43 times higher than that of MIL-R-27208, Variable Wirewound Resistor.

One other part type for which λ_b changed considerably was MIL-R-11804, Fixed Power Film Resistor. The failure rate for this part was reduced by a factor of 15 as a result of the ranking process. Although this part is large in size and somewhat different in construction, its base failure rate should not be significantly higher than the worst of the other fixed resistors. It was given higher environmental factors in the dynamic environments (see section 3.1.2).

Although no data were collected on MIL-R-39002 (RK style resistors), this base failure rate was changed to be the same as that for MIL-R-19. These two specifications presently have the same base failure rate in MIL-HDBK-217B and no reason was determined to make them different. Therefore, when MIL-R-19 was changed as a result of the data analysis, MIL-R-39002 also was changed.

In a similar manner, MIL-R-22684 and MIL-R-39017 (RL and RLR styles) were changed to maintain the same general ranking with respect to MIL-R-10509 and MIL-R-55182 (RN and RNR styles) as reflected by MIL-HDBK-217B. Because of their basic construction, the insulated film resistors (RL and RLR) should have a slightly lower failure rate that the RN/RNR film resistors as indicated in the Handbook. Therefore, the base failure rate for these resistors was lowered by the same factor determined by analysis of RN/RNR data.

Insufficient data were collected on the two new models shown in Table 11 to derive quantitative base failure rates. Therefore, a ranking process had to be used. Both resistor types, MIL-R-39023 (RQ) and MIL-R-23285 (RVC), are non-wirewound variable resistors. The RVC style resistors have a film resistance element shaped in an arc with the construction being metal-ceramic film fused onto a ceramic substrate. The RQ style is a precision device having a

resistance element usually consisting of carbon, cermet, or conductive plastic deposited on a plastic insulating base. The RQ was ranked slightly better in terms of reliability because it utilizes better overall construction techniques including body sealing and it is built on a precision assembly line where more in-process testing is usually performed.

TABLE 11

Summary of Recommended Revisions to MIL-HDBK-217B
Resistor Base Failure Rates (λ_b)

Specification	Recommended Change to λ_b in MIL-HDBK-217B	Criteria for Determining λ_b
MIL-R-27208 RT MIL-R-39015 RTR	No change	-
MIL-R-22097 RJ MIL-R-39035 RJR	Divide by 22	Data
MIL-R-39023 RQ	New	Ranked
MIL-R-23285 RVC	New	Ranked
MIL-R-94 RV	Divide by 2.5	Data
MIL-R-19 RA	Divide by 0.9	Data
MIL-R-39002 RK	Divide by 0.9	Ranked
MIL-R-22 RP	No change	-
MIL-R-12934 RR	No change	-
MIL-R-11 RC MIL-R-39008 RCR	No change	-
MIL-R-22684 RL MIL-R-39017 RLR	Divide by 2	Ranked
MIL-R-10509 RN MIL-R-55182 RNR	Divide by 2	Data
MIL-R-93 RB MIL-R-39005 RBR	No change	-
MIL-R-18546 RE MIL-R-39009 RER	Divide by 2	Data
MIL-R-26 RW MIL-R-39007 RWR	Divide by 0.64	Data
MIL-R-11804 RD	Divide by 15	Ranked

The model used in MIL-HDBK-217B for calculating resistor base failure rates is:

$$\lambda_b = Ae^{B\left(\frac{T + 273}{N_T}\right)^G} e^{\left[\left(\frac{S}{Ns}\right)\left(\frac{T + 273}{273}\right)^J\right]^H}$$

where,

A is an adjustment factor for each type of resistor to adjust the model to the appropriate failure rate level

e is the natural logarithm base, 2.718

T is the ambient operating temperature (degrees C)

N_T is a temperature constant

B is a shaping parameter

G, H, J are acceleration constants

N_S is a stress constant

S is the electrical stress and is the ratio of operating power to rated power.

The values for the constants are given in MIL-HDBK-217B for each resistor type. Three of these constants were changed during this study for some part types: A, B, and N_T. The quantitative values of N_T in MIL-HDBK-217B reflect the part temperature at which derating begins plus 273°C for most fixed resistors and a few potentiometers. Origin of the N_T values for the other part types could not be determined. Therefore, these values were changed to have the same derivation as the majority. The values of B were also changed to maintain the same overall failure rate value. Where changes were recommended for the base failure rates, the adjustment factor, A, was changed. Table 12 lists the part specifications for which constants in the base failure rate model were changed and gives the new values. The table also gives all the constant values for the two potentiometers not in MIL-HDBK-217B.

3.1.2 Environmental Factors

The environmental factors, Π_E, for resistors have undergone extensive revisions as depicted in Table 10. Sufficient data for evaluation of differences in the effects of environments were collected on four different environments: ground fixed (G_F), airborne inhabited (A_I), naval sheltered (N_S), and ground mobile (G_M). The data collected during the study effort were used as a revision baseline from which additional changes were made to those environments or part types on which little or no data were collected. The airborne environment was expanded to four categories to separate the effects of supersonic aircraft such as fighters from other types of aircraft such as transports and heavy bombers.

TABLE 12

Revisions to Constants in Base Failure Rate Model

Part Type		Revised Constant Values						
Style	Specification	A	B	N_T	G	N_S	H	J
RD	MIL-R-11804	7.33E-03*	0.202*	298.000*	2.600	1.450	1.300	0.890
RE RER	MIL-R-18546 MIL-R-39009	1.50E-04*	2.640	298.000	1.000	0.466	1.000	1.000
RL RLR	MIL-R-22684 MIL-R-39017	3.25E-04*	1.000	343.000	3.000	1.000	1.000	1.000
RN RNR	MIL-R-10509 MIL-R-55182	5.00E-05*	3.500	398.000	1.000	1.000	1.000	1.000
RW RWR	MIL-R-26 MIL-R-39007	1.48E-03*	1.000	298.000	2.000	0.500	1.000	1.000
RK	MIL-R-39002	3.98E-02*	1.050*	358.000*	5.280	1.440	1.000	4.460
RJ RJR	MIL-R-22097 MIL-R-39035	1.90E-02*	0.445*	358.000*	7.300	2.690	1.000	2.460
RP	MIL-R-22	4.81E-02	0.334*	298.000*	4.660	1.470	1.000	2.830
RR	MIL-R-12934	7.35E-02	1.030*	358.000*	4.450	2.740	1.000	3.510
RT RTR	MIL-R-27208 MIL-R-39015	6.20E-03*	1.000	358.000	5.000	1.000	1.000	1.000
RV	MIL-R-94	2.46E-02*	0.459*	343.000*	9.300	2.320	1.000	5.300
RVC	MIL-R-23285**	2.57E-02	1.000	398.000	7.900	2.450	1.000	4.300
RQ	MIL-R-39023**	1.80E-02	1.000	343.000	7.400	2.550	1.000	3.600
RA	MIL-R-19	3.98E-02*	0.514*	313.000*	5.280	1.440	1.000	4.460

*Revised value
**New line entry

One basic decision was made initially concerning the difference between the effects of the S_F/G_B environment and the G_F environment. The ratio of the Π_E factors between these two environments for a given part type varies from 2 to 10 in MIL-HDBK-217B. A study of the differences among the various part types could not justify such a wide variation. Both the S_F/G_B and G_F environments are rather stable with the G_F allowing more temperature and humidity variation; however this variation is normally not too extreme. In fact, the G_F environments on which data were collected in this study were air-conditioned and would not be considered much more severe than S_F/G_B. A similar result relating the similarities between the G_B and most G_F environments

is reported in Reference 4 where a data collection effort was also performed. Therefore, it appeared that the effects on resistor base failure rates of the G_F environment should be approximately the same for all resistor types and not more than a factor of 2 or 3 worse than the S_F/G_B environment. Thus, a factor of 3 was assigned to the resistor types more susceptible to humidity and/or temperature problems, and a factor of 2 given to the remaining types. The Π_E factor for G_B and S_F remained at one for all resistors.

As explained in section 2.2, General Analysis Procedure, the relative differences between the different environments were quantitatively evaluated whenever possible. The factors thus obtained were scaled to a G_F factor of 2 or 3, whichever was applicable, without changing the ratios between any of the factors.

Several general guidelines were followed in developing the revised environmental factors, particularly when no observed data were available to use. Part types more susceptible to humidity, such as compositions, should have higher factors in environments of potentially high humidity than the less susceptible part types. MIL-R-94, Variable Composition Resistor, was given the highest factors of any non-wirewound because it generally has no end seal and is of single turn construction which makes it more unstable than other types. Wirewound resistors are usually more prone to failure in dynamic environments than non-wirewound because of the internal weld construction and the possibility of turn-to-turn shorts. The accurate wirewound fixed resistors, MIL-R-93 and MIL-R-39005, should have the highest factors of the fixed resistors in dynamic environments because of their many turns that increase the probability of shorts. MIL-R-11804, Power Film Resistor, is more susceptible to failures in dynamic environments than most part types because of its large size and the materials used in its construction (usually glass and ceramic).

One of the most significant changes resulting from the data analysis is a reduction in the N_S factor. The revised N_S factors vary from approximately one-half to one-tenth of the N_S factors presently in MIL-HDBK-217B. One reason for this reduction may be the inclusion of submarine data in the N_S category. An attempt was made to create a separate submarine factor, but insufficient data were available to substantiate doing this. Therefore, the data were combined and designated as N_S.

The aircraft environment was expanded to four categories to separate supersonic aircraft from other types. It is generally accepted that equipment on supersonic aircraft are exposed to higher levels of shock, vibration, and acoustic noise, and to a more severe operating temperature range than equipment on other aircraft. Also the mission duration is usually much shorter for supersonic aircraft, thereby creating more cyclic problems. Therefore, significant differences in reliability would be expected and have been observed. In this study program, only three part types (all capacitors) had sufficient data in both environments for comparisons to be made. The values

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4. Pearce, M.B. and Rise, G.D., "Technique for Developing Equipment Failure Rate K Factors," Boeing Aerospace Company, December 1973.

derived from these parts are shown in Table 13 along with the results observed from two other efforts involving reliability data collection (References 4 and 5). The factor of 2.1 given in the table from Reference 5 was obtained from an analysis of data in that report. The factors from Reference 4 were taken directly from the report. Both references only isolated failures to the equipment or line replaceable unit (LRU) level.

TABLE 13

Equipment/Part MTBF Variations by Aircraft Type

Source	MTBF Factor by Aircraft			
	Fighter	Military Transport	Bomber	Commercial Transport
Martin Marietta study:				
Capacitor CK style	1.7	1	-	-
Capacitor CL style	3.5	1	-	-
Capacitor CS style	6.8	1	-	-
Reference 5	2.1	1	-	-
Reference 4	2	1	1.5	0.14

Since only a small quantity of data were available at the part level, it was decided that a general factor should be developed which could be applied to all part types. This would be a multiplicative factor to be applied to the subsonic values to obtain the supersonic environmental values. A review of the factors in Table 13 indicated that a value of 2 would be a good general factor to differentiate between subsonic and supersonic. Therefore, this value was selected to be used in determining the appropriate environmental factors for supersonic aircraft. The term supersonic aircraft includes fighters and interceptors, while the subsonic category encompasses transports, heavy bombers, cargo, and patrol aircraft.

The G_F, A_I, and N_S environmental factors were changed to varying degrees based primarily upon analysis of the collected data. The G_M environment was represented by less data; therefore, fewer factors were changed for this environment. The only potentiometer having a significant quantity of data in the G_M environment was MIL-R-94 (RV style). Analysis of this data indicated that the G_M factor should be changed from 50 to 23. Although this factor was

5. Kern, G.A., and Drnas, I.M., "Operational Influences on Reliability," page 5-4, Hughes Aircraft Company, RADC-TR-76-366, December 1976.

lowered by a significant amount, there did not appear to be any basis for changing other potentiometer factors since the revised RV value was still higher than other G_M factors. Therefore, no other potentiometer G_M factors were changed.

For fixed resistors, data on MIL-R-26 (RW style) indicated a change in the G_M factor from 10 to 5. Since this was significantly lower than any other fixed resistor factors, the other resistors were reviewed to determine if there was any justification for reducing their G_M factors. After studying the construction and electrical characteristics of the other fixed resistors with respect to the RW style, it was determined that for the G_M environment the only resistors that should have higher factors were the RD and RB/RBR styles. Therefore, the other fixed resistor G_M factors were adjusted to reflect these findings.

Little or no data were collected in three environments: naval unsheltered (N_U), airborne uninhabited (A_U), and missile launch (M_L). Therefore, with the exception of three part classes, the factors in MIL-HDBK-217B were retained for these environments since there were no data to justify a change. One exception is the values for the RL/RLR styles which were changed to be the same as the factors for RN/RNR resistors because of the great similarity between these part types. The values of the N_U, A_{UT}, and A_{UF} factors for the RV style potentiometer were evaluated and determined to be inconsistent with those for the other potentiometers. Therefore, these values were reduced by a factor of 2.2 as this was the adjustment factor used in section 2.2.4 to reduce the G_F, N_S, and G_M factors to their final values. Similarly, the RB/RBR style factors for the N_U, A_{UT}, A_{UF}, and M_L environments were not realistic when compared to the other fixed wirewound resistors. These factors were lowered accordingly, but remained the highest of the wirewound types because the problem with shorts in dynamic environments.

The A_U factors in the Handbook were assumed to depict the subsonic (A_{UT}) environments, and the supersonic (A_{UF}) environmental factors were obtained by multiplying the A_{UT} factors by two. It should be noted that in some cases, the A_{UF} factors are in the same range as the M_L factors. This is not unrealistic because the A_{UF} environment is more severe than M_L in some categories such as temperature cycling and possibly vibration. In addition, supersonic aircraft maneuvers can apply severe acceleration forces to equipment.

3.1.3 Resistor Network Model

Although insufficient data were collected on resistor networks to validate a detailed failure rate model, an interim model was developed based upon appropriate sections of the hybrid failure rate models and an engineering evaluation of resistor network part characteristics.

The failure rate model developed for resistor networks, MIL-R-83401, is as follows:

$$\lambda_P = (N_R\lambda_R + N_I\lambda_I + \pi_{PF}\lambda_{PF})\ \pi_E\ \pi_Q$$

where:

N_R is the number of film resistors in use

λ_R is the film resistor failure rate and is determined as:

$$\lambda_R = \pi_{TECH}\ \lambda_{RB}\ \pi_T$$

where:

π_{TECH} = 1 for thick film

= 2 for thin film

λ_{RB} = 4 x 10^{-5} failures/10^6 hr

π_T is found from Table 14

N_I is the number of interconnections and is determined by the number of leads plus the number of internal connections

λ_I is the interconnection failure rate and is found from Table 15

π_{PF} = 1 for MIL-R-83401/04 and /05 (SIP)

= 1.5 for MIL-R-83401/03 (FLATPACK)

= 2 for MIL-R-83401/01 and /02 (DIP)

λ_{PF} = 0.005 failures /10^6 hr

π_E is found from Table 16

π_Q = 1 for MIL quality

= 30 for lower quality.

TABLE 14

π_T versus Temperature

$T_P(^oC)$	π_T	$T_P(^oC)$	π_T	$T_P(^oC)$	π_T
25	1.0	70	4.5	115	14.0
30	1.2	75	5.2	120	16.0
35	1.5	80	6.0	125	18.0
40	1.7	85	6.8	130	20.0
45	2.1	90	7.8	135	22.0
50	2.4	95	8.8	140	24.0
55	2.8	100	10.0	145	27.0
60	3.3	105	11.0	150	29.0
65	3.9	110	13.0		

Note:

$$\pi_T = \text{Exp}\left[-3411\left(\frac{1}{T_P + 273} - \frac{1}{298}\right)\right]$$

where T_P is package temperature in ^oC.

TABLE 15

λ_I as a Function of Temperature

$T_P(^oC)$	λ_I	$T_P(^oC)$	λ_I	$T_P(^oC)$	λ_I
25	0.00008	70	0.00048	115	0.00188
30	0.00010	75	0.00057	120	0.00215
35	0.00012	80	0.00067	125	0.00244
40	0.00015	85	0.00078	130	0.00277
45	0.00019	90	0.00092	135	0.00314
50	0.00023	95	0.00107	140	0.00354
55	0.00028	100	0.00123	145	0.00398
60	0.00033	105	0.00143	150	0.00446
65	0.00040	110	0.00164		

$$\lambda_I = (8.0 \times 10^{-5})\ \text{Exp}\left[\left(\frac{-0.350}{K}\right)\left(\frac{1}{T_P + 273} - \frac{1}{298}\right)\right]$$

where $K = 8.63 \times 10^{-5}$
and T_P is package temperature in ^oC.

TABLE 16

Environmental Factor, π_E

Environmental	π_E
G_B	1
S_F	1
G_F	2
A_{IT}	4
A_{IF}	8
N_S	4
G_M	4
N_U	6
A_{UT}	6
A_{UF}	12
M_L	11

This model is based on a sum of three failure rate contributors:

1 Resistor elements

2 Interconnections

3 Package.

The first contributor, $N_R\ \lambda_R$, is the failure rate contribution of the resistor elements themselves. It is temperature dependent through the π_T factor which is based on network package temperature. Package temperature is a function of ambient temperature and the temperature rise, varying with package style, and results from the power dissipated in the network. The temperature dependence is based on that given for hybrids in MIL-HDBK-217B when package temperature is known.

If package temperature is not known, it may be estimated as follows:

$T_P = T_a + \Delta T$

where:

T_a is ambient temperature in the immediate vicinity of the network

$\Delta T = K_S P_D$

where:

K_S is given in Table 17

P_D is power dissipated in the network in watts.

TABLE 17

K_S Values by Network Style

Style	K_S*
RZ010	64
RZ020	55
RZ030	66
RZ040	52
RZ050	45

*K_S is in ^oC/watt

The difference in base failures rates for thick and thin film technologies (either allowed by the specification) is accounted for in the π_{TECH} factor. The thin film resistors are more susceptible to failure due to anomolies in the substrate and film deterioration. Thick films are inherently stable, but are subject to flaking, particularly when subjected to temperature cycling.

The second failure contributor is the interconnection term, $N_I \lambda_I$. The failure rate of the interconnections is temperature dependent as described in the revised microelectronics hybrid failure rate model proposed for MIL-HDBK-217B (Reference 6). This proposed model was reviewed and found to apply to the pertinent networks after the multiplying constant was adjusted from 1.7 X 10^{-4} to 8 X 10^{-5} to reflect the simpler and more reliable interconnections that exist in the networks.

There are many variations in the methods and processes that can be employed in the design and manufacture of the networks under MIL-R-83401. Therefore, the number of internal connections varies with style, manufacturer, and circuit schematic type. These interconnections can be of several types in-

Reference 6. "Military Standardization Handbook for Reliability Prediction," MIL-HDBK-217B, Notice 2 (Proposed), Table 2.1.7-1, Rome Air Development Center, 1 August 1977.

cluding wire and solder connections. Wires used for internal interconnection (unlikely in thick film implementation but possible with thin films) must be counted when determining the interconnection failure rate term. The sandwich construction of some packages includes interconnections from top to bottom levels which must be included in the count of interconnections.

Package failures are included in the $\pi_{PF}\ \lambda_{PF}$ contribution. The simplest package, the SIP, is given the normalized π_{PF} factor of 1, while the DIP and flatpack packages are allotted a higher probability of failure due to their construction. These package factor values were taken from the MIL-HDBK-217B hybrid model. The base value of package failure rate is an adjusted value of that given in the hybrid model to reflect the simpler packages for the networks.

Environmental and quality factors, π_E and π_Q respectively, are applied directly to the sum of the three failure rate contributors, as shown in the resistor network model equation. The values for the environmental factors are based upon those given in the proposed new hybrid model, except they have been normalized to a value of 1.0 for the G_B environment to be consistent with the environmental factors for the other resistor types.

3.1.4 Thermistor Failure Rate Revision

The changes to the failure rate model for thermistors, MIL-T-23648, consisted of the addition of rod types. This includes the styles RTH 12, 14, 16, 18, 20, 22 and 42.

Thermistor data were difficult to classify as to which type was being referred to in the data descriptions and reports obtained for this study. Also, no stress data were available with a sufficient number of failures to use as a basis for constructing a new model based on stress and temperature. Therefore, the rod types were allocated failure rates as a result of an evaluation of their construction and complexity relative to the bead and disk types. The new types are included in Table 18.

3.1.5 Variable Resistor Model Revision

The present method for calculating the failure rate for a potentiometer involves the calculation of the stress ratio, S, from Tables 2.5.7-1, 2.5.7-2, 2.5.7-3, and 2.5.7-4 of MIL-HDBK-217B. The formula given for S in Table 2.5.7-1 is:

$$S = \frac{P_{applied}}{\pi_{eff} \times \pi_{ganged} \times P_{rated}}$$

where the π_{eff} factor is the correction factor for electrical loading on the wiper contact. The value of π_{eff} is calculated from the formula:

$$\pi_{eff} = \frac{R_L^2}{R_L^2 + K_H(R_P^2 + 2\ R_P R_L)}$$

where R_P = potentiometer resistance and

R_L = load resistance.

A new method for calculation of S is needed when the potentiometer is connected as a rheostat. An attempt to use the present model with $R_L = 0$ (rheostat connection) gives a value of 0 for π_{eff} which makes S undefined.

TABLE 18

Revised Thermistor Failure Rates

Environment	Predicted Failure Rate (Failures/10^6 Hrs)		
	Bead Type Style RTH 24, 26, 28, 30, 32, 34, 36, 38 to 40	Disk Type Style RTH 6, 8, 10	Rod Type Style RTH 12, 14, 16, 18, 20, 22, 42; MIL-T-23648A /4 through /9,/19
G_B	0.021	0.065	0.105
S_F	0.021	0.065	0.105
G_F	0.100	0.310	0.500
G_M	0.520	1.600	2.600
N_S	0.300	0.900	1.500
N_U	0.400	1.200	2.000
A_{IT}	0.250	0.750	1.250
A_{IF}	0.500	1.500	2.250
A_{UT}	0.340	1.000	1.700
A_{UF}	0.680	2.000	3.400
M_L	1.200	3.600	6.000

The potentiometer used in a rheostat application will have a known maximum current rating. This may be given directly in the specification or can be calculated from the formula:

$$I_{max\ rated} = \sqrt{\frac{P_{rated}}{R_P}}$$

where P_{rated} is power rating of the potentiometer with the full resistance engaged and R_P is the nominal resistance of the potentiometer. From circuit considerations, the particular application will determine a maximum operating current which will pass through the rheostat, generally at minimum resistance. By using the maximum operating current ($I_{op\ max}$), the stress ratio for a rheostat application can be calculated:

$$S_R = \frac{(I_{op\ max})^2}{\pi_{ganged} \times (I_{max\ rated})^2} .$$

This reflects the power stress at different settings of the rheostat assuming that the power dissipation over any section of the resistance element is limited to an amount proportional to the amount of element engaged.

It is recommended that the formula for S_R be added to the general model for variable resistors in MIL-HDBK-217B. This formula would then be used for calculating stress under a rheostat application while the existing stress formula would be used when the potentiometers are applied in the 3-terminal configuration.

3.2 Capacitor Analysis Results

Twenty-six capacitor specifications were analyzed, 17 of which are in MIL-HDBK-217B. Table 19 lists the 26 specifications covered in this study. Table 20 lists the nine specifications not in the present Handbook, some of which are not current but included because of the large number of equipments still in field use which contain these parts. Table 21 shows recommended revisions to the base failure rates and environmental factors, along with the respective values presently given in MIL-HDBK-217B. The base failure rates are for a 30°C temperature and a 0.30 stress ratio of operating to rated voltage.

In Table 21 the specifications are grouped when both Military Standard and Established Reliability versions are available. Base failure rates are the same for each pair since the quality factors are used to differentiate between different levels of reliability within a given part type. The abbreviations for environments in the table are consistent with those in MIL-HDBK-217B, except for the airborne category which has been expanded from two to four categories to distinguish between supersonic and subsonic aircraft. Table 21 assumes that the environmental factors in MIL-HDBK-217B represent the subsonic environment.

TABLE 19

Capacitor Specifications to be Included in Revision to MIL-HDBK-217B

Part Specification	Style	Description*
Fixed Capacitors		
MIL-C-5	CM	Mica
MIL-C-20	CC/CCR	Ceramic, Temperature Compensating, ER and Non-ER
MIL-C-25	CP	Paper
MIL-C-62	CE	Aluminum, Dry
MIL-C-3965	CL	Tantalum, Non-Solid
MIL-C-10950	CB	Mica, Button Style
MIL-C-11015	CK	Ceramic, General Purpose
MIL-C-11272	CY	Glass
MIL-C-11693	CZ	Paper, Metallized Paper, Metallized Plastic, RFI Feed-thru, ER and Non-ER
MIL-C-12889	CA	Paper, RFI Bypass
MIL-C-14157	CPV	Paper, Paper-Plastic, ER and Non-ER
MIL-C-18312	CH	Metallized Paper, Paper-Plastic, Plastic
MIL-C-19978	CQ/CQR	Plastic, Paper-Plastic, ER and Non-ER
MIL-C-23269	CYR	Glass, ER
MIL-C-39001	CMR	Mica, ER
MIL-C-39003	CSR	Tantalum, Solid, ER
MIL-C-39006	CLR	Tantalum, Non-Solid, ER
MIL-C-39014	CKR	Ceramic, General Purpose, ER
MIL-C-39018	CU	Aluminum Oxide
MIL-C-39022	CHR	Metallized Paper-Plastic, Plastic, ER
MIL-C-55514	CFR	Plastic, Metallized Plastic, ER
MIL-C-83421	CRH	Super-Metallized Plastic, ER
Variable Capacitors		
MIL-C-81	CV	Ceramic
MIL-C-92	CT	Air, Trimmer
MIL-C-14409	PC	Piston, Tubular Trimmer
MIL-C-23183	CG	Vacuum or Gas, Fixed and Variable

*ER refers to Established Reliability

TABLE 20

Capacitor Specifications to be Added to MIL-HDBK-217B

Specification	Style	Description
MIL-C-25	CP	Fixed, Paper
MIL-C-92	CT	Variable, Air, Trimmer
MIL-C-11693	CZ	Fixed, Paper, Metallized Paper, Metallized Plastic, RFI Feed-Thru, ER + Non-ER
MIL-C-12889	CA	Fixed, Paper, RFI Bypass
MIL-C-23183	CG	Variable and Fixed, Vacuum or Gas
MIL-C-55514	CFR	Plastic, Metallized Plastic, ER
MIL-C-83421	CRH	Super-Metallized, ER
MIL-C-11272	CY	Glass
MIL-C-18312	CH	Metallized Paper, Paper-Plastic, Plastic

TABLE 21

Comparison of Revised Capacitor Base Failure Rates and Environmental Factors with MIL-HDBK-217B Values

Part Type		Base Failure Rate (λ_b)		Environmental Factors																			
				G_B/S_F		G_F		A_{IT}		A_{IF}		N_S		G_M		N_U		A_{UT}		A_{UF}		M_L	
Specification	Style	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev	217B	Rev
Rigid Dielectric																							
MIL-C-11272 MIL-C-23269	CY CYR	0.0007	0.00018	1	1	4	2	6	6	-	12	6	5	6	6	14	14	24	24	-	48	30	30
MIL-C-5 MIL-C-39001	CM CMR	0.0001	0.00024	1	1	4	2	6	6	-	12	6	2.5	6	6	14	14	24	24	-	48	30	30
MIL-C-20	CC/CCR	0.0013	0.00094	1	1	4	2	6	6	-	12	6	2.5	6	6	18	18	24	24	-	48	30	30
MIL-C-11015** MIL-C-39014**	CK CKR	0.0038	0.0013	1	1	2	2	4	12	-	24	4	2.5	4	4	8	8	10	10	-	20	15	15
MIL-C-10950	CB	0.0114	0.0114	1	1	4	2	6	6	-	12	6	3	6	6	17.5	13	24	24	-	48	30	30
Film Dielectric																							
MIL-C-19978**	CQ/CQR	0.00007	0.00063	1	1	2	2	4	4	-	8	4	4	4	4	9	9	15	15	-	30	20	20
MIL-C-14157**	CPV	0.00007	0.00063	1	1	2	2	4	4	-	8	4	4	4	4	9	9	15	15	-	30	20	20
MIL-C-83421	CRH	*	0.00069	*	1	*	2	*	4	-	8	*	4	*	4	*	9	*	15	-	30	*	20
MIL-C-18312** MIL-C-39022**	CH CHR	0.00007	0.0009	1	1	2	2	4	4	-	8	4	4	4	4	9	9	15	15	-	30	20	20
MIL-C-12889	CA	*	0.0012	*	1	*	2	*	5	-	10	*	4	*	5	*	11	*	18	-	36	*	25
MIL-C-25	CP	*	0.0012	*	1	*	2	*	5	-	10	*	4	*	5	*	11	*	18	-	36	*	25
MIL-C-55514	CFR	*	0.0014	*	1	*	2	*	5	-	10	*	4	*	7	*	15	*	20	-	40	*	30
MIL-C-11693	CZ	*	0.0015	*	1	*	2	*	5	-	10	*	4	*	5	*	11	*	18	-	36	*	25
Electrolytic																							
MIL-C-3965 MIL-C-39006	CL CLR	0.0068	0.0030	1	1	2	2	6	15	-	30	6	6	6	12	14	14	20	20	-	40	30	30
MIL-C-39003	CSR	0.0053	0.0058	1	1	2	2	4	8.5	-	17	4	2.5	4	4	9	9	15	15	-	30	20	20
MIL-C-39018	CU	0.014	0.0108	1	1	2	2	12	12	-	24	12	6	12	12	20	20	30	30	-	60	40	40
MIL-C-62	CE	0.0225	0.0150	1	1	2	2	12	12	-	24	12	6	12	12	20	20	30	30	-	60	40	40
Variable																							
MIL-C-14409	PC	0.0249	0.0128	0.1	1	0.3	3	1	8	-	16	1	7	1	7	5	19	8	40	-	80	12	56
MIL-C-81	CV	0.0131	0.0196	1	1	4	4	8	8	-	16	8	8	8	8	24	24	50	50	-	100	70	70
MIL-C-92	CT	*	0.0314	*	1	*	4	*	8	-	16	*	8	*	8	*	24	*	50	-	100	*	70
MIL-C-23183	CG	*	0.0980	*	1	*	4	*	12	-	24	*	8	*	12	*	32	*	75	-	150	*	N/A

*Specification not in MIL-HDBK-217B.
**Failure rate for style having T = 125°C maximum rated temperature.
Note: All failure rates calculated for T = 30°C and voltage stress ratio of 0.3.

3.2.1 Base Failure Rates

From Table 21 a comparison can be made of the recommended revision for each capacitor base failure rate, λ_b, to the existing failure rates in MIL-HDBK-217B. Revisions were based upon analyses of collected field operating data or, where insufficient data were available, upon ranking methodology. The base failure rate for the CL/CLR style capacitors will be modified in the total part failure rate model by the addition of a new multiplicative factor. This factor, termed a construction factor, is discussed in section 3.2.4.1 and separates the CL/CLR style capacitors into five distinct groups.

Table 22 gives the quantitative change to be applied to the base failure rates in MIL-HDBK-217B to derive the revised rates. Also given in the table are criteria used for changing the existing failure rate. Where ranking was the criterion used, this process was performed after all changes were determined that resulted from the data analyses. The ranking process consisted of both mechanical and electrical engineering evaluations of the part characteristics compared with the parts for which data were available.

In the rigid dielectric group only one specification was ranked: MIL-C-20, Temperature Compensating Ceramic Capacitor. The base failure rate for this capacitor was lowered as a result of the new base failure rate derived from the data for General Purpose Ceramic Capacitors, MIL-C-11015 and MIL-C-39014. The temperature compensating capacitors have a more stable dielectric than the general purpose types and should have a lower failure rate. Therefore, the MIL-C-20 failure rates were reduced to keep them lower than the general purpose ceramic part failure rates.

For the film dielectric group, six capacitor types were ranked because of insufficient data. Five of these are new additions to the Handbook. The CPV style (MIL-C-14157) failure rate was increased by the same factor as the CQ/CQR styles (MIL-C-19978). These two specifications presently use the same base failure rate tables in MIL-HDBK-217B because of their similarities. When the CQ/CQR failure rates were changed as a result of the data analyses, the CPV values were likewise changed.

The CRH style capacitor (MIL-C-83421) was ranked having a lower failure rate than the CHR style (MIL-C-39022). The CRH parts have a higher insulation resistance that increases their reliability. This style is new and may prove to have a lower failure rate than the CQR style. However, because of the CRH style being new, it was ranked with a slightly higher failure rate.

The CA and CP styles (MIL-C-12889 and MIL-C-25 respectively) were ranked with failure rates slightly worse than the CHR capacitors. The CA and CP styles were given the same base failure rate because both capacitors have sealed construction and similar dielectrics. The CFR style (MIL-C-55514) was considered similar in reliability to the CA and CP styles, except that it is not sealed and is metallized in many versions. Therefore, the CFR was ranked with a slightly lower reliability. The CZ style (MIL-C-11693) was considered to be the worst of the film dielectric capacitors since it also has metallized versions and has a more complicated termination system than straight axial lead types such as MIL-C-25.

TABLE 22

Summary of Recommended Revisions to MIL-HDBK-217B Capacitor Base Failure Rates (λ_b)

Part Type		Recommended Change to λ_b in MIL-HDBK-217B	Criteria for Determining λ_b
Specification	Style		
Rigid Dielectric			
MIL-C-11272 MIL-C-23269	CY CYR	Divide by 4.0	Data
MIL-C-5 MIL-C-39001	CM CMR	Divide by 0.8	Data
MIL-C-20	CC/CCR	Divide by 1.4	Ranked
MIL-C-11015 MIL-C-39014	CK CKR	Divide by 3.0	Data
MIL-C-10950	CB	No change	-
Film Dielectric			
MIL-C-19978	CQ/CQR	Divide by 0.11	Data
MIL-C-14157	CPV	Divide by 0.11	Ranked
MIL-C-83421	CRH	New	Ranked
MIL-C-18312 MIL-C-39022	CH CHR	Divide by 0.08	Data
MIL-C-12889	CA	New	Ranked
MIL-C-25	CP	New	Ranked
MIL-C-11693	CZ	New	Ranked
MIL-C-55514	CFR	New	Ranked
Electrolytic			
MIL-C-3965 MIL-C-39006	CL CLR	Divide by 2.3	Data
MIL-C-39003	CSR	Divide by 0.8	Data
MIL-C-39018	CU	Divide by 1.3	Ranked
MIL-C-62	CE	Divide by 1.5	Data
Variable			
MIL-C-14409	PC	Divide by 2.0	Ranked
MIL-C-81	CV	Divide by 0.67	Data
MIL-C-92	CT	New	Ranked
MIL-C-23183	CG	New	Ranked

The ranking process was used on only one capacitor in the fixed electrolytic group: MIL-C-39018, Aluminum Oxide. This capacitor has a high performance dielectric system which makes it more reliable than the dry aluminum type, MIL-C-62. Therefore, when the dry aluminum capacitor base failure rate was reduced as a result of data analyses, the aluminum oxide base failure rate was also reduced.

In the variable capacitor group, only the MIL-C-81 (CV style) capacitors had sufficient data from which to determine a base failure rate. As a result, the other three styles were ranked in comparison to the CV style. The variable piston capacitor, MIL-C-14409, was considered to be more reliable than the CV style because it is usually sealed and consists of an air or glass dielectric, either of which is better than the ceramic in the CV type. The CT style (MIL-C-92) is more prone to contamination due to its open plate construction and was given a higher failure rate than the CV style.

The CG style (MIL-C-23183) vacuum or gas variable capacitor is significantly more complex and fragile than the other variable capacitors. The construction of a typical high voltage vacuum variable capacitor consists of two sets of concentric cylinders, one on a sliding shaft and the other fixed, which are enclosed in an evacuated ceramic or glass envelope with copper anodes located at both ends. A flexible metal bellows, attached to a sliding sleeve type bearing, maintains the vacuum while allowing the capacitance to be varied. The linear sliding motion required to vary capacitance is converted to rotary tuning by a threaded shaft. In the variable configuration, this capacitor was given the highest base failure rate of any capacitor. This capacitor can also be obtained in a fixed configuration which would be more reliable than the variable. The general failure rate model for the CG style capacitor will include a multiplicative factor for part configuration which will have a value of 0.1 for the fixed version and 1.0 for the variable.

The general model used in MIL-HDBK-217B for calculating capacitor base failure rates (λ_b) is:

$$\lambda_b = A\left[\left(\frac{S}{N_S}\right)^H + 1\right] e^{B\left(\frac{T+273}{N_T}\right)^G}$$

where:

A is an adjustment factor for each different type of capacitor, to adjust the model to the proper failure rate

S represents the ratio of operating to rated voltage

N_S is a stress constant

e is the natural logarithm base, 2.718

T is the operating ambient temperature in degrees Centigrade

N_T is a temperature constant

B is a shaping parameter

G and H are acceleration constants.

The capacitor styles for which the model constants are revised are listed with their new values in Table 23. New specifications to be added to the Handbook are also shown in the table. Changes were made to A, B, and N_T for many of the existing specifications based on the results of this study program. For most parts the quantitative values of N_T in MIL-HDBK-217B reflect the part temperature at which derating begins plus 273°C. Origin of the N_T values for the other part types could not be determined. Therefore, these values were changed to be consistent with the derivation method of the majority. The values of B were also changed to maintain the same overall failure rate value. Multiple entries are given in Table 23 for part types having styles with different temperature limits. Where changes were recommended for the base failure rates, the adjustment factor, A, was changed.

TABLE 23

Revisions to Constants in Capacitor Base Failure Rate Model

Part Type		Model Constants						
Style	Specification	Temp Limit (°C)	A	B	N_T	G	N_S	H
Fixed Capacitors								
CA	MIL-C-12889**	85	8.6×10^{-4}	2.5	358	18.0	0.4	5
CB	MIL-C-10950	85	5.3×10^{-3}	1.2*	358*	6.3	0.4	3
CB	MIL-C-10950**	150	5.3×10^{-3}	1.2	423	6.3	0.4	3
CC CCR	MIL-C-20	85	2.6×10^{-9}*	14.3*	358*	1.0	0.3	3
CC CCR	MIL-C-20**	125	2.6×10^{-9}	14.3	398	1.0	0.3	3
CE	MIL-C-62	85	2.8×10^{-3}*	4.09*	358*	5.9	0.55	3
CFR	MIL-C-55514**	85	9.9×10^{-4}	2.5	358	18.0	0.4	5
CFR	MIL-C-55514**	125	9.9×10^{-4}	2.5	398	18.0	0.4	5

*Revised value
**New line entry

TABLE 23 (Cont)

Part Type			Model Constants					
Style	Specification	Temp Limit (°C)	A	B	N_T	G	N_S	H
Fixed Capacitors (Cont)								
CH CHR	MIL-C-18312** MIL-C-39022	85	6.9×10^{-4}*	2.5	358	18.0	0.4	5
CH CHR	MIL-C-18312** MIL-C-39022	125	6.9×10^{-4}*	2.5	398	18.0	0.4	5
CK CKR	MIL-C-11015 MIL-C-39014	85	3.0×10^{-4}*	1.0	358	1.0	0.3	3
CK CKR	MIL-C-11015 MIL-C-39014	125	3.0×10^{-4}*	1.0	398	1.0	0.3	3
CK	MIL-C-11015	150	3.0×10^{-4}*	1.0	423	1.0	0.3	3
CL	MIL-C-3965**	85	1.65×10^{-3}	2.6	358	9.0	0.4	3
CL CLR	MIL-C-3965 MIL-C-39006	125	1.65×10^{-3}*	2.6*	398*	9.0	0.4	3
CL CLR	MIL-C-3965** MIL-C-39006**	175	1.65×10^{-3}	2.6	448	9.0	0.4	3
CM	MIL-C-5**	70	8.60×10^{-10}	16.0	343	1.0	0.4	3
CM	MIL-C-5**	85	8.60×10^{-10}	16.0	358	1.0	0.4	3
CM CMR	MIL-C-5 MIL-C-39001	125	8.60×10^{-10}*	16.0	398	1.0	0.4	3
CM CMR	MIL-C-5** MIL-C-39001**	150	8.60×10^{-10}	16.0	423	1.0	0.4	3
CP	MIL-C-25**	85	8.6×10^{-4}	2.5	358	18.0	0.4	5
CP	MIL-C-25**	125	8.6×10^{-4}	2.5	398	18.0	0.4	5
CPV CQ CQR	MIL-C-14157 MIL-C-19978	65	5.0×10^{-4}*	2.5	338	18.0	0.4	5
CPV CQ CQR	MIL-C-14157 MIL-C-19978	85	5.0×10^{-4}*	2.5	358	18.0	0.4	5
CPV CQ CQR	MIL-C-14157 MIL-C-19978	125	5.0×10^{-4}*	2.5	398	18.0	0.4	5

*Revised value
*New line entry

TABLE 23 (Cont)

Part Type			Model Constants					
Style	Specification	Temp Limit (°C)	A	B	N_T	G	N_S	H
Fixed Capacitors (Cont)								
CQ CQR	MIL-C-19978**	170	5.0×10^{-4}	2.5	443	18.0	0.4	5
CRH	MIL-C-83421**	125	5.5×10^{-4}	2.5	398	18.0	0.4	5
CSR	MIL-C-39903	85	3.75×10^{-3}*	1.0*	358	9.0	0.4	3
CSR	MIL-C-39003**	125	3.75×10^{-3}	1.0	398	9.0	0.4	3
CU	MIL-C-39018	125	2.54×10^{-3}*	5.09*	398*	5.0	0.5	3
CY CYR	MIL-C-11272** MIL-C-23269	125	8.25×10^{-10}*	16.0	398	1.0	0.5	4
CY	MIL-C-11272**	200	8.25×10^{-10}	16.0	473	1.0	0.5	4
CZ	MIL-C-11693**	85	1.15×10^{-3}	2.5	358	18.0	0.4	5
CZ	MIL-C-11693**	125	1.15×10^{-3}	2.5	398	18.0	0.4	5
CZ	MIL-C-11693**	150	1.15×10^{-3}	2.5	423	18.0	0.4	5
Variable Capacitors								
CG	MIL-C-23183**	85	1.12×10^{-2}	1.59	358	10.1	0.17	3
CG	MIL-C-23183**	100	1.12×10^{-2}	1.59	373	10.1	0.17	3
CT	MIL-C-92**	85	1.92×10^{-6}	10.8	358	1.0	0.33	3
CV	MIL-C-81	85	2.24×10^{-3}*	1.59*	358*	10.1	0.17	3
CV	MIL-C-81**	125	2.24×10^{-3}	1.59	398	10.1	0.17	3
PC	MIL-C-14409**	125	7.3×10^{-7}	12.1	398	1.0	0.33	3
PC	MIL-C-14409	150	7.3×10^{-7}*	12.1*	423*	1.0	0.33	3

* Revised value
** New line entry

3.2.2 Environmental Factors

Sufficient data were collected for the quantitative evaluation of environmental effects for five environments: ground fixed (G_F), airborne inhabited (A_I), naval sheltered (N_S), naval unsheltered (N_U) and ground mobile (G_M). The majority of changes were made to the G_F and N_S environments. As with the resistors, the airborne environment was expanded to separate the effects of supersonic and subsonic aircraft. The recommended factors for all part types are shown in Table 21 along with the values presently in MIL-HDBK-217B.

Using the same rationale described in the resistor environmental factor section, the G_F factors for all fixed capacitors were given a value of 2. This was not a great change for any part types as most factors were already 2 and the highest factor was 4.

The environmental factor for ground benign (G_B) remained at 1.0 for all part types. One variable capacitor, MIL-C-14409, previously had a G_B factor of 0.1. This was changed to 1.0 to be consistent with the other part types. The other factors for this particular capacitor were also changed to be in the right perspective with the factors for MIL-C-81, the other variable capacitor given in MIL-HDBK-217B.

As was the case for resistors, the N_S environment including submarine data was lowered for many part types. Only one part type, MIL-C-10950 (button mica) had sufficient data in the N_U environment to justify a change. The N_U factor for this part type was lowered from 17.5 to 13.

As a result of the data collected, the subsonic airborne inhabited (A_{IT}) environmental factors were changed for three part types. The factor for ceramic capacitors, CK/CKR styles, was increased from 4 to 12, and the solid tantalum capacitor (CSR style) factor was also increased from 4 to 8.5. The data on non-solid tantalum capacitors (CL/CLR styles) also indicated that their A_{IT} factor should be increased. This reinforces other findings for this part such as those in Reference 7 which indicate these capacitors are subject to internal lead breakage in high random vibration environments. Therefore, the A_{IT} factor for CL/CLR parts was increased from 6 to 15.

The airborne supersonic factors for both inhabited and uninhabited (A_{IF} and A_{UF} respectively) environments were obtained by multiplying their respective subsonic factors by 2. The resistor section (3.1.2) gives the data and references from which this value of 2 was determined.

The data for CL/CLR style capacitors also indicated that the MIL-HDBK-217B G_M factor should be increased, but not as high as A_{IT}. This factor was changed to 12 from the original value of 6.

Reference 7. Dalton, Robert P., "Usage Constraints for Tantalum Foil Capacitors," Evaluation Engineering, March-April 1977.

Insufficient data were collected in the airborne uninhabited and missile launch environments to justify any revisions. Therefore, the factors given in MIL-HDBK-217B were retained.

The factors for the new specifications were based primarily upon the factors given for similar part types in MIL-HDBK-217B. The CRH style factors were considered to be the same as those for the CHR type. The new film dielectric styles (CA, CP, CZ, and CFR) were considered to be similar to the CQR style except worse in dynamic environments. The CFR style is also more susceptible to humidity problems since it is not hermetically sealed. The new variable capacitors were considered to be similar to the CV style except for the CG part type, which is more failure prone in dynamic environments and was given higher factors.

3.2.3 Quality Factors

Analysis of the data indicated that changes should be made to some of the quality factors. All changes except one related to the Military Standard (non-ER) grade and the L level of the Established Reliability (ER) grade. The one exception was the elimination of the Upper grade on all non-ER specifications because of the lack of a clear definition for this category. The specifications with revised quality factors are listed in Table 24. The factors for three groups of parts are based upon data collected: CY/CYR, CK/CKR, and CL/CLR. The other changes were made as a result of analyzing the group inspection tests given in the individual specifications.

TABLE 24

Quality Factor Revisions for MIL-HDBK-217B

Part Type		Quality Levels						
Specification	Style	Non-ER	L	M	P	R	S	T
MIL-C-11272 (Non-ER) MIL-C-23269 (ER)	CY CYR	3	3	1.0	0.3	0.1	0.03	-
MIL-C-5 (Non-ER) MIL-C-39001 (ER)	CM CMR	3*	1.5	1.0	0.3	0.1	0.03	0.01
MIL-C-20 (Non-ER and ER)	CC/CCR	3	-	1.0	0.3	0.1	0.03	-
MIL-C-11015 (Non-ER) MIL-C-39014 (ER)	CK CKR	3	3	1.0	0.3	0.1	0.03	-
MIL-C-19978 (Non-ER and ER)	CQ/CQR	10	3	1.0	0.3	0.1	0.03	-
MIL-C-14157 (ER)	CPV	-	-	1.0	0.3	0.1	0.03	-
MIL-C-18312 (Non-ER) MIL-C-39022 (ER)	CH CHR	7	3	1.0	0.3	0.1	0.03	-
MIL-C-83421 (ER)	CRH	-	-	1.0	0.3	0.1	0.03	-
MIL-C-55514 (ER)	CFR	-	-	1.0	0.3	0.1	0.03	-
MIL-C-11693 (Non-ER and ER)	CZ	3	-	1.0	-	-	-	-
MIL-C-3965 (Non-ER) MIL-C-39006 (ER)	CL CLR	3	1.5	1.0	0.3	0.1	0.03	-

*For MIL-C-5: Dipped = 3
Molded = 6

The highest factor, 10, given in Table 24 is for MIL-C-19978 (CQ style) capacitors. This is the same factor given in MIL-HDBK-217B since no justification could be found for changing it. An examination of the group inspection tests for MIL-C-19978 indicates that there is a significant difference between

the ER and non-ER quality levels, a finding which supports the Handbook value. A summary of the group inspection tests for this specification is given in Table 25 which shows the testing philosophy for each quality level, i.e., whether no testing, sampling tests, or 100 percent of the parts are tested. As indicated by the table, there is no accelerated burn-in for non-ER parts, while 100 percent of the level M ER parts are burned-in. Also, only sampling tests are performed at the non-ER level for seal, insulation resistance, temperature cycling, and three other tests, while 100 percent of the parts are subjected to these tests at the ER level. There are other variations between some of the tests in Table 25, such as different AQL levels and sample size. To maintain simplicity these variations are not given in the table, although they were considered in the analyses. This simplification also applies to the other tables in this section which present similar data.

TABLE 25

Group Inspection Tests versus Quality Levels for
MIL-C-19978 (CQ/CQR) Capacitors

Inspection Tests	Quality Levels (MIL-C-19978)			
	Non-ER	L	M	PRS
Group A Inspection:				
Burn-In (Accelerated)	None	Sample	100%	100%
Radiographic	None	None	None	100%
Temperature Cycling	Sample	100%	100%	100%
Seal	Sample	100%	100%	100%
Dielectric Withstanding Voltage	Sample	100%	100%	100%
Insulation Resistance	Sample	100%	100%	100%
Capacitance	Sample	100%	100%	100%
Dissipation Factor	Sample	100%	100%	100%
Visual and Mechanical (external)	Sample	Sample	Sample	Sample
Group B Inspection:				
Subgroup 1*	Sample	Sample	Sample	Sample
Life (240 hrs)	Sample	Sample	Sample	Sample
Extended Life (5760 hrs)	None	Sample	None	None
Group C Inspection:				
Subgroups 1-4*	Sample	Sample	Sample	Sample
Resistance to Solvents	None	Sample	Sample	Sample
Resistance to Soldering Heat	None	Sample	Sample	Sample

*These tests are similar for all quality levels

The L level factor for MIL-C-19978 (CQR style) was changed to 3 from 1.5 for two reasons, the burn-in and X-ray tests. Only a sample of the L level parts are burned-in versus 100 percent of the other ER level parts. In addition, no X-ray is done at the L level, while the P, R, and S levels are 100 percent X-rayed. No X-ray test is performed on any M level parts. This specification and only one other examined showed a significant difference in testing between the M level and other ER level parts. The other specification was MIL-C-39003 (CSR style) which also X-rayed only the P, R, and S levels.

A quality factor of 7 was given to the MIL-C-18312 (CH style) capacitors. An evaluation of the group inspection tests shown in Table 26 indicates significant differences in X-ray, temperature cycling, and several other tests between CH and CHR styles (MIL-C-39022). However, since there was no burn-in test at any quality level, the difference between non-ER and ER should not be as wide as that given for MIL-C-19978. Therefore, a value of 7 was given to this quality level. The L level was changed from 1.5 to 3 by using the same reasoning given for MIL-C-19978.

The factor of 3 determined for ceramic capacitors (CK style) was based upon analyses of collected data. However, an examination of the group inspection tests in Table 27 supports the data results. The major differences are in thermal shock and the group B and C life tests. The other tests are quite similar; in fact, some sampling tests performed at the non-ER level are not performed at all on ER parts such as dielectric withstanding voltage and capacitance. Therefore, the factor should be much lower than the values for the CQ and CH style capacitors. The non-ER and ER level L parts were given the same factor because of the similarities in their group inspection tests.

The other revisions given in Table 24 were based upon similar evaluations of the group inspection tests. Where only small differences between the L and M level tests were indicated, the factor of 1.5 given in MIL-HDBK-217B was retained.

An additional ER quality level has been included in Table 24. The mica capacitor specification (MIL-C-39001) includes the T level which is a lower failure rate level than S. The same relative ratio between the M, P, R, and S levels was maintained in determining the T factor.

No changes have been made to the M, P, R, or S quality levels for any of the part types. A large quantity of data is required at these high reliability levels in order to generate realistic failure rates. Only two part types had data at the S level which included failures. Ceramic capacitors (MIL-C-39014) had three failures at the S level in the G_B environment, and non-solid tantalum capacitors (MIL-C-39006) had one failure in the same environment. Neither part type had sufficient data at any other quality grade in the G_B environment to allow direct comparisons to be made. Therefore, a rough comparison of the S level to the Military Standard level was made by normalizing the G_B data to other environments. The results indicated that the relative difference between S level and the Military Standard level may be closer to 10 to 1 for these two part types than the 100 to 1 factor given

in Table 24. However, definite conclusions cannot be drawn from such insufficient data, and further study should be done in this area before any changes are made to the Handbook. More data at the higher quality levels need to be accumulated and analyzed.

TABLE 26

Group Inspection Tests versus Quality Levels for MIL-C-18312 (CH) and MIL-C-39022 (CHR) Capacitors

Inspection Tests	Quality Levels		
	Non-ER	L	MPRS
Group A Inspection:			
Radiographic	None	Sample	100%
Temperature Cycling	None	Sample	100%
Seal	Sample	Sample	100%
Dielectric Withstanding Voltage	Sample	Sample	100%
Insulation Resistance	Sample	Sample	100%
Capacitance	Sample	Sample	100%
Dissipation Factor	Sample	Sample	100%
Visual and Mechanical (external)	Sample	Sample	Sample
Group B Inspection:			
Insulation Resistance	Sample	Sample	None
Barometric Pressure	Sample	Sample	None
Life	Sample (250 hrs)	Sample (2,000 hrs)	None
Group C Inspection:			
Subgroups 1A-1D*	None	Sample	Sample
Subgroups 1-3*	Sample	None	None
Barometric Pressure	None	None	Sample
Life	Sample (750 hrs)	None	Sample (2,000 hrs)
Insulation Resistance	None	None	Sample

*These are similar tests for the ER and Non-ER levels

TABLE 27

Group Inspection Tests versus Quality Levels for MIL-C-11015 (CK) and MIL-C-39014 (CKR) Capacitors

Inspection Tests	Quality Levels		
	Non-ER	L	MPRS
Group A Inspection:			
Radiographic	None	None	100% (S level only, selected styles)
Thermal Shock and Voltage Conditioning	None	None	100%
Thermal Shock	None	Sample	None
Visual and Mechanical (external)	Sample	Sample	Sample
Seal (selected styles)	Sample	Sample	None
Dielectric Withstanding Voltage	Sample	None	None
Insulation Resistance	Sample	None	None
Capacitance	Sample	None	None
Dissipation Factor	Sample	None	None
Group B Inspection:			
Voltage - Temperature Limits	Sample	None	None
Life	Sample (250 hrs)	Sample (250 hrs)	None
Group C Inspection:			
Life	Sample (2,000 hrs)	None	Sample (4,000 hrs)
Other Tests*	Sample	Sample	Sample

*These tests are similar for all quality levels

3.2.4 Additional Revisions and Analyses

3.2.4.1 Non-Solid Tantalum Capacitors

In addition to the revisions in the base failure rate and environmental factors, a new factor for construction is recommended for the non-solid tantalum capacitor (MIL-C-3965 and MIL-C-39006) failure rate model. Package and internal construction techniques vary significantly among the different types of capacitors included in these two specifications. The anode element can consist of etched or plain tantalum foil or a sinterered tantalum slug. The case may be hermetic or nonhermetic and be made from tantalum, silver, or some other corrosion-resisting metal. The electrolyte can be either liquid, jell, or paste.

Since all variations in the construction and materials used in these capacitors can have a significant effect upon reliability, it did not seem logical to have only one failure rate to cover the different part variations. In order to improve the reliability prediction accuracy, a construction factor has been added to the existing failure rate model for these parts. The nomenclature and quantitative values associated with this factor are given in Table 28.

To avoid making the construction factor too complex for practical usage, only the primary variations in part types were considered. The hermetically sealed foil types were taken as a standard and given a value of 1.0 because most of the collected data fell into this category. The other factors were based upon qualitative analyses. The all-tantalum version was considered to be significantly better than the others because it eliminates metal migration problems.

TABLE 28

MIL-C-3965/MIL-C-39006 Construction Factor

Construction Type	π_C
Slug, All Tantalum	0.3
Foil, Hermetic*	1.0
Slug, Hermetic*	2.0
Foil, Non-Hermetic*	2.5
Slug, Non-Hermetic*	3.0

*Type of seal identified as follows:

1 MIL-C-3965 (CL) - Note last letter in part number:

G = Hermetic

E = Non-Hermetic

Example: CL10BC700TPG is hermetic

2 MIL-C-39006 (CLR) - Consult individual part specification sheet (slash sheet)

Note:

Foil Types - CL 20, 21, 22, 23, 30, 31, 32, 33, 51, 52, 53, 54, 70, 71, 72, 73

CLR 25, 27, 35, 37, 53, 71, 73

Slug Types - CL 10, 13, 14, 16, 17, 18, 55, 56, 66, 67

CLR 10, 14, 17, 65, 69, 89

All Tantalum - CLR 79

`.2.4.2 Capacitance Factor

A new factor, π_{CV}, which varies as a function of the part capacitance value, has been developed for the fixed capacitors. This is not a totally new factor to MIL-HDBK-217B as MIL-C-23269 (glass capacitors) presently has a π_{CV} factor in its model. The need for this factor for all fixed capacitors was determined after researching the subject in literature and direct contact with manufacturers and contractors. Results indicated that the higher capacitance devices failed more frequently, a logical result considering that dielectric breakdown is one of the primary causes of capacitor failure. As the capacitance value increases, the dielectric area also increases, thereby enhancing the probability of dielectric failure. In addition to the increase in dielectric area, the thickness of the dielectric is reduced in some types of capacitors after the capacitance increases to certain levels, making the part more vulnerable to punch-through failures. Vendors try to offset the increased probability of shorts caused by higher capacitance by use of different design techniques such as a thicker separation between the foils in foil type capacitors. However, the fact remains that since reliability is affected by capacitance value, this should be considered in the failure rate models.

Once the need for a capacitance factor was established, it was necessary to determine the magnitude of the factor. Some sources contacted felt that failure rate should vary directly with the increase in dielectric area, i.e., if the area increased by a factor of 1000, so would the failure rate. However, some capacitor failure modes, such as dissipation factor and capacitance change, are not significantly affected by capacitance rating. In fact, opens are actually more likely to occur in some small package (low capacitance) devices because the end terminations are more fragile than in larger packages. Therefore, it was decided that one order of magnitude variation in failure rate from the lowest capacitance value to the highest value for a given part type would be more realistic.

The range of one order of magnitude was established to represent the worst case situation. Since some types of capacitors are more susceptible to failure than others, the π_{CV} range should vary significantly between part types. In order to rank the part types by the relative percentage of failures caused by dielectric problems versus other causes, all available capacitor failure mode information was researched. The GIDEP ALERT data file was used as a primary source for this type of data. The results of this effort are presented in Table 29. Also given in the table are the resulting maximum ranges for π_{CV} established for each part class.

The worst case value of 10 was applied to the aluminum electrolytic capacitors for which about 75 percent of the failures were dielectric problems. The lowest range of 2 was assigned to the nonsolid tantalum (CL/CLR style) capacitors that had no dielectric problems in the data analyzed. It was felt that, with more data, the relative percentage for CL/CLR capacitors would still be less than 20 percent. This is in agreement with the industry contacts who were of the opinion that open failures in the lower capacitance packages of this style tended to offset the increased shorts in the larger packages. Leakage is the biggest problem with this capacitor

TABLE 29

π_{CV} Ranges Resulting from Percent Dielectric Problems

Capacitor Style/Family	%Failures by Dielectric	π_{CV} Range*
Aluminum Electrolytic (CE/CU)	75	10.0
Solid Tantalum (CSR)	50	5.0
Rigid Dielectric Family	50	5.0
Film Dielectric Family	20	2.5
Nonsolid Tantalum (CL/CLR)	0	2.0

*Ratio of the highest to the lowest π_{CV} factor used for each part style.

style. Data on CK style capacitors were assumed to be representative of all rigid dielectric capacitors. In a like manner, data results for CQ and CHR style capacitors were extended to include all film dielectric capacitors.

The range of minimum to maximum capacitance for the various part types varies considerably as shown in Table 30. The lowest capacitance is the 0.1 pF for the CC/CCR style ceramic capacitors while the highest is 220,000 μF for the CU style aluminum electrolytics. These capacitance values were obtained from the individual slash sheets for each appropriate specification.

The next task was to define a relationship between capacitance and π_{CV}. It was decided that π_{CV} should have a value of 1.0 somewhere between the mid-point and the lower end of the capacitance spectrum for each part type, since the failure rates were based upon data clustered at that end of the spectrum. Therefore, for a given part type, π_{CV} would have a value less than 1.0 at the low end of the capacitance range and be greater than 1.0 at the high end.

The method utilized to assign values to π_{CV} as a function of capacitance was based upon a logarithmic relationship as shown in Figure 1, where it appears linear in a logarithmic representation. The example shown in Figure 1 represents the relationship derived for CU style (MIL-C-39018) capacitors. The general equation for this function is of the form:

$$\pi_{CV} = AC^m$$

where: A = Value of π_{CV} at C = 1.0

C = Capacitance

m = Slope of the function.

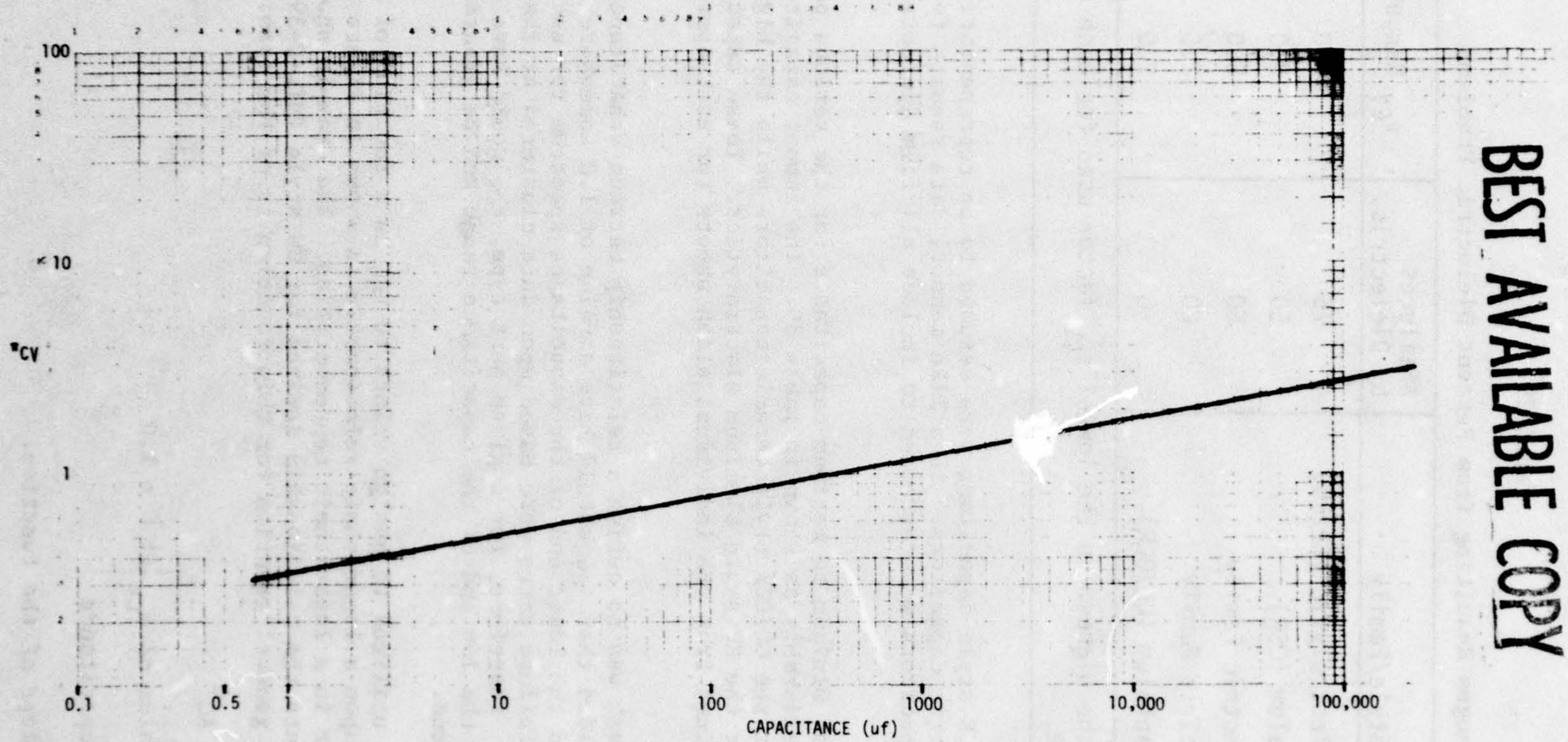


Figure 1. Π_{CV} Factor versus Capacitance for Aluminum Electrolytic Capacitors (Style CU)

TABLE 30

Range of Maximum and Minimum Capacitance

Style	Specification	C_{min}	C_{max}
CA	MIL-C-12889	0.01 μF	0.5 μF
CB	MIL-C-10950	5.0 pF	5,100.0 pF
CC/CCR	MIL-C-20	0.1 pF	100,000.0 pF
CE	MIL-C-62	1.0 μF	150,000.0 μF
CFR	MIL-C-55514	0.001 μF	50.0 μF
CH CHR	MIL-C-18312 MIL-C-39022	0.001 μF	22.0 μF
CK CKR	MIL-C-11015 MIL-C-39014	2.2 pF	3.3 μF
CL CLR	MIL-C-3965 MIL-C-39006	0.1 μF	3,500.0 μF
CM CMR	MIL-C-5 MIL-C-39001	1.0 pF	100,000.0 pF
CP	MIL-C-25	0.001 μF	16.0 μF
CPV	MIL-C-14157	0.001 μF	1.0 μF
CQ/CQR	MIL-C-19978	0.0001 μF	15.0 μF
CRH	MIL-C-83421	0.001 μF	22.0 μF
CSR	MIL-C-39003	0.001 μF	1,000.0 μF
CU	MIL-C-39018	0.68 μF	220,000.0 μF
CY CYR	MIL-C-11272 MIL-C-23269	0.1 pF	10,000.0 pF
CZ	MIL-C-11693	0.001 μF	2.0 μF

Use of this equation assigns the value, $\pi_{CV} = 1.0$, to the logarithmic mid-point of the capacitance range which is between the mid-point and minimum value on a rectangular scale. The values of m and A must be determined for each capacitor type, depending upon the capacitance range and the π_{CV} range given in Table 29.

The value of m can be calculated by using the equation for slope:

$$m = \text{slope} = \frac{\log \pi_{CV\,(max)} - \log \pi_{CV\,(min)}}{\log C_{(max)} - \log C_{(min)}} .$$

The values for maximum and minimum capacitance ($C_{(max)}$ and $C_{(min)}$) can be obtained from Table 30. This equation can be further simplified by defining the following relationship:

$$N = \frac{\pi_{CV(max)}}{\pi_{CV(min)}}$$

where N = values in Table 29.

Using this relationship, the numerator of the equation for m can be simplified in the following manner:

$$\log \pi_{CV(max)} - \log \pi_{CV(min)} = \log \frac{\pi_{CV(max)}}{\pi_{CV(min)}} = \log N.$$

The equation for the slope, m, then becomes:

$$m = \frac{\log N}{\log C_{(max)} - \log C_{(min)}} .$$

In order to evenly spread the values of π_{CV} around the value of 1.0, the following relationship was defined:

$$\pi_{CV(min)} = \frac{1}{\pi_{CV(max)}} .$$

Using this relationship in conjunction with that defined for N, the values for the highest and lowest π_{CV} factors ($\pi_{CV(max)}$ and $\pi_{CV(min)}$) can be obtained:

$$\pi_{CV(max)} = \sqrt{N}$$

$$\pi_{CV(min)} = \frac{1}{\sqrt{N}} .$$

At the minimum capacitance value, $C_{(min)}$, for any given part type, the capacitance factor is also at its lowest value, $\pi_{CV(min)}$. Therefore, using this relationship, the value of A can be determined:

$$\pi_{CV} = AC^m$$

$$A = \frac{\pi_{CV}}{C^m}$$

$$A = \frac{\pi_{CV(min)}}{(C_{min})^m}$$

$$A = \frac{1}{\sqrt{N}\ (C_{(min)})^m} .$$

To summarize, the method for calculating the values for the capacitance factor, π_{CV}, is to solve the following equation:

$$\pi_{CV} = AC^m$$

where: $$A = \frac{1}{\sqrt{N}\,(C_{(min)})^m}$$

C = capacitance value

$$m = \frac{\log N}{\log C_{(max)} - \log C_{(min)}}$$

N = Values in Table 29.

Using this procedure, values for π_{CV} have been calculated for all fixed capacitors except the CA style (MIL-C-12889). As evidenced by the values in Table 30, the capacitance range for CA capacitors was too small to consider a π_{CV} factor. Values for π_{CV} in intervals of 0.1 are shown in Table 31 for all other fixed capacitors.

TABLE 31

Values of Capacitance Factor, π_{CV}, for All Capacitor Styles

Capacitance Factor π_{CV}	Capacitor Style*					
	CY/CYR	CM/CMR	CC/CCR	CSR	CB	CPV
0.3	-	-	-	-	-	-
0.4	≤ 0.1pF	≤ 1.0pF	≤ 0.11pF	≤ 0.0011μF	≤ 5.1pF	-
0.5	>0.1pF ≤ 0.44pF	>1.0pF ≤ 4.4pF	>0.11pF ≤ 0.59pF	>0.0011μF ≤ 0.0059μF	>5.1pF ≤ 12pF	-
0.6	>0.44pF ≤ 1.5pF	>4.4pF ≤ 15pF	>0.59pF ≤ 2.5pF	>0.0059μF ≤ 0.025μF	>12pF ≤ 25pF	≤ 0.0012μF
0.7	>1.5pF ≤ 4.0pF	>15pF ≤ 40pF	>2.5pF ≤ 8.5pF	>0.025μF ≤ 0.085μF	>25pF ≤ 46pF	>0.0012μF ≤ 0.0036μF
0.8	>4.0pF ≤ 9.9pF	>40pF ≤ 99pF	>8.5pF ≤ 25pF	>0.085μF ≤ 0.25μF	>46pF ≤ 79pF	>0.0036μF ≤ 0.0093μF
0.9	>9.9pF ≤ 22pF	>99pF ≤ 220pF	>25pF ≤ 64pF	>0.25μF ≤ 0.64μF	>79pF ≤ 130pF	>0.0093μF ≤ 0.021μF
1.0	>22pF ≤ 45pF	>220pF ≤ 450pF	>64pF ≤ 150pF	>0.64μF ≤ 1.5μF	>130pF ≤ 200pF	>0.021μF ≤ 0.046μF
1.1	>45pF ≤ 86pF	>450pF ≤ 860pF	>150pF ≤ 330pF	>1.5μF ≤ 3.3μF	>200pF ≤ 290pF	>0.046μF ≤ 0.091μF
1.2	>86pF ≤ 160pF	>860pF ≤ 1600pF	>330pF ≤ 680pF	>3.3μF ≤ 6.8μF	>290pF ≤ 420pF	>0.091μF ≤ 0.17μF
1.3	>160pF ≤ 270pF	>1600pF ≤ 2700pF	>680pF ≤ 1300pF	>6.8μF ≤ 13μF	>420pF ≤ 580pF	>0.17μF ≤ 0.30μF
1.4	>270pF ≤ 450pF	>2700pF ≤ 4500pF	>1300pF ≤ 2400pF	>13μF ≤ 24μF	>580pF ≤ 790pF	>0.30μR ≤ 0.52μF
1.5	>450pF ≤ 730pF	>4500pF ≤ 7300pF	>2400pF ≤ 4300pF	>24μF ≤ 43μF	>790pF ≤ 1100pF	>0.52μF ≤ 0.86μF
1.6	>730pF ≤ 1100pF	>7300pF ≤ 0.011μF	>4300pF ≤ 7400pF	>43μF ≤ 74μF	>1100pF ≤ 1400pF	>0.86μF
1.7	>1100pF ≤ 1700pF	>0.011μF ≤ 0.017μF	>7400pF ≤ 0.012μF	>74μF ≤ 120μF	>1400pF ≤ 1800pF	-
1.8	>1700pF ≤ 2600pF	>0.017μF ≤ 0.026μF	>0.012μF ≤ 0.020μF	>120μF ≤ 200μF	>1800pF ≤ 2300pF	-
1.9	>2600pF ≤ 3800pF	>0.026μF ≤ 0.038μF	>0.020μF ≤ 0.031μF	>200μF ≤ 310μF	>2300pF ≤ 2800pF	-
2.0	>3800pF ≤ 5400pF	>0.038μF ≤ 0.054μF	>0.031μF ≤ 0.047μF	>310μF ≤ 470μF	>2800pF ≤ 3500pF	-
2.1	>5400pF ≤ 7600pF	>0.054μF ≤ 0.076μF	>0.047μF ≤ 0.071μF	>470μF ≤ 710μF	>3500pF ≤ 4300pF	-
2.2	>7600pF	>0.076μF	>0.071μF	>710μF	>4300pF	-
2.3	-	-	-	-	-	-

*Capacitance values shown are arithmetic solutions for C in the equation, $\pi_{CV} = AC^m$, and do not necessarily represent actual capacitor values.

TABLE 31 Continued

Capacitance Factor π_{CV}	Capacitor Style*				
	CU	CFR	CL/C-R	CH/CHR	CK/CKR
0.3	≤ 1.19μF	-	-	-	-
0.4	>1.19μF ≤ 4.75μF	-		-	≤ 2.3pF
0.5	>4.75μF ≤ 14.35μF	-	-	-	>2.3pF ≤ 14pF
0.6	>14.35μF ≤ 36.0μF	≤ 0.0014μF	-	≤ 0.0013μF	>14pF ≤ 60pF
0.7	>36.0μF ≤ 79.3μF	>0.0014μF ≤ 0.0075μF	≤ 0.24μF	>0.0013μF ≤ 0.0064μF	>60pF ≤ 210pF
0.8	>79.3μF ≤ 158μF	>0.0075μF ≤ 0.033μF	>0.24μF ≤ 1.6μF	>0.0064μF ≤ 0.025μF	>210pF ≤ 640pF
0.9	>158μF ≤ 292μF	>0.033μF ≤ 0.120μF	>1.6μF ≤ 8.6μF	>0.025μF ≤ 0.085μF	>640pF ≤ 1700pF
1.0	>292μF ≤ 506μF	>0.120μF ≤ 0.40μF	>8.6μF ≤ 39μF	>0.085μF ≤ 0.250μF	>1700pF ≤ 4100pF
1.1	>506μF ≤ 835 F	>0.40μF ≤ 1.2μF	>39μF ≤ 150μF	>0.250μF ≤ 0.680μF	>4100pF ≤ 9300pF
1.2	>835μF ≤ 1320μF	>1.2μF ≤ 3.1μF	>150μF ≤ 540μF	>0.680μF ≤ 1.7μF	>9300pF ≤ 0.019μF
1.3	>1320μF ≤ 2020μF	>3.1μF ≤ 7.7μF	>540μF ≤ 1700μF	>1.7μF ≤ 3.9μF	>0.019μF ≤ 0.038μF
1.4	>2020μF ≤ 3000μF	>7.7μF ≤ 18μF	>1700μF	>3.9μF ≤ 8.6μF	>0.038μF ≤ 0.072μF
1.5	>3000μF ≤ 4330μF	>18μF ≤ 40μF	-	>8.6μF	>0.072μF ≤ 0.13μF
1.6	>4330μF ≤ 6110μF	>40μF	-	-	>0.130μF ≤ 0.22μF
1.7	>6110μF ≤ 8440μF	-	-	-	>0.22μF ≤ 0.38μF
1.8	>8440μF ≤ 11500μF	-	-	-	>0.38μF ≤ 0.62μF
1.9	>11500μF ≤ 15300μF	-	-	-	>0.62μF ≤ 0.98μF
2.0	>15300μF ≤ 20200μF	-	-	-	>0.98μF ≤ 1.5μF
2.1	>20200μF ≤ 26300μF	-	-	-	>1.5μF ≤ 2.3μF
2.2	>26300μF ≤ 33700μF	-	-	-	>2.3μF
2.3	>33700μF ≤ 42900μF	-	-	-	-
2.4	>42900μF ≤ 53900μF	-	-	-	-
2.5	>53900μF ≤ 67200μF	-	-	-	-
2.6	>67200μF ≤ 83100μF	-	-	-	-
2.7	>83100μF ≤ 102000μF	-	-	-	-
2.8	>102000μF ≤ 124000μF	-	-	-	-
2.9	>124000μF ≤ 150000μF	-	-	-	-
3.0	>150000μF	-	-	-	-

*Capacitance values shown are arithmetic solutions for C in the equation, $\pi_{CV} = AC^m$, and do not necessarily represent actual capacitor values.

TABLE 31 Continued

Capacitance Factor π_{CV}	Capacitor Style*				
	CE	CRH	CQ/CQR	CZ	CP
0.3	≤ 1.7µF	-	-	-	-
0.4	>1.7µF ≤ 6.2µF	-	-	-	-
0.5	>6.2µF ≤ 18µF	-	-	-	-
0.6	>18µF ≤ 42µF	≤ 0.0013µF	≤ 140pF	≤ 0.0013µF	≤ 0.0013µF
0.7	>42µF ≤ 87µF	>0.0013µF ≤ 0.0064µF	>140pF ≤ 920pF	>0.0013 F ≤ 0.0041µF	>0.0013µF ≤ 0.0061µF
0.8	>87µF ≤ 170µF	>0.0064µF ≤ 0.025µF	>920pF ≤ 0.0047µF	>0.0041 F ≤ 0.012µF	>0.0061µF ≤ 0.023µF
0.9	>170µF ≤ 300µF	>0.025µF ≤ 0.085µF	>0.0047µF ≤ 0.020µF	>0.012 F ≤ 0.029µF	>0.023µF ≤ 0.074µF
1.0	>300µF ≤ 500µF	>0.085µF ≤ 0.25µF	>0.020µF ≤ 0.073µF	>0.029 F ≤ 0.067µF	>0.074µF ≤ 0.21µF
1.1	>500µF ≤ 800µF	>0.25µF ≤ 0.68µF	>0.073µF ≤ 0.24µF	>0.067µF ≤ 0.14µF	>0.21µF ≤ 0.55µF
1.2	>800µF ≤ 1200µF	>0.68µF ≤ 1.7µF	>0.24µF ≤ 0.71µF	>0.14µF ≤ 0.28µF	>0.55µF ≤ 1.3µF
1.3	>1200µF ≤ 1800µF	>1.7µF ≤ 3.9µF	>0.71µF ≤ 1.9µF	>0.28µF ≤ 0.54µF	>1.3µF ≤ 3.0µF
1.4	>1800µF ≤ 2700µF	>3.9µF ≤ 8.6µF	>1.9µF ≤ 4.9µF	>0.54µF ≤ 0.98µF	>3.0µF ≤ 6.4µF
1.5	>2700µF ≤ 3700µF	>8.6µF ≤ 18µF	>4.9µF ≤ 12µF	>0.98µF ≤ 1.7µF	>6.4µF ≤ 13µF
1.6	>3700µF ≤ 5200µF	>18µF	>12µF	>1.7µF	>13µF
1.7	>5200µF ≤ 7000µF	-	-	-	-
1.8	>7000µF ≤ 9400µF	-	-	-	-
1.9	>9400µF ≤ 12000µF	-	-	-	-
2.0	>12000µF ≤ 16000µF	-	-	-	-
2.1	>16000µF ≤ 20000µF	-	-	-	-
2.2	>20000µF ≤ 26000µF	-	-	-	-
2.3	>26000µF ≤ 32000µF	-	-	-	-
2.4	>32000µF ≤ 40000µF	-	-	-	-
2.5	>40000µF ≤ 49000µF	-	-	-	-
2.6	>49000µF ≤ 60000µF	-	-	-	-
2.7	>60000µF ≤ 73000µF	-	-	-	-
2.8	>73000µF ≤ 88000µF	-	-	-	-
2.9	>88000µF ≤ 100000µF	-	-	-	-
3.0	>100000µF	-	-	-	-

*Capacitance values shown are arithmetic solutions for C in the equation, $\pi_{CV} = AC^m$, and do not necessarily represent actual capacitor values.

3.2.4.3 Capacitor Ripple Current

This section deals with the effects of ripple on capacitor failure rates. The effect of ripple on capacitor temperature was studied in particular and it was determined that temperature rise can be significant. Methods were sought to quantify this heat rise for inclusion in the Handbook.

3.2.4.3.1 Effects of Ripple Current

Ripple current effects influence reliability in capacitors to varying degrees depending on the capacitor type. Ripple can influence capacitor reliability in two ways, namely, 1) by the internal heat generated as a result of the losses in the capacitor, and 2) by the ripple voltage which is superimposed on any dc voltage present and therefore is a component of the applied operating voltage.

The amount of heat generated in a capacitor by the applied ac component is a result of the current flowing through the equivalent series resistance (ESR) of that capacitor. The heat generated is equal to the value of the ESR times the square of the current. The current is determined by the voltage applied (its frequency and amplitude) and the impedance of the capacitor.

A capacitor is often represented by its equivalent circuit (Figure 2). The impedance of a capacitor is:

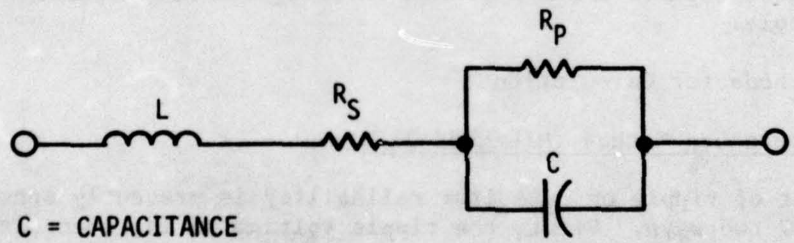
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

where

R is the ESR

X_L is the inductive reactance (arising from leads, plates, etc.)

X_C is the capacitive reactance.



C = CAPACITANCE

R_S = SERIES RESISTANCE (LEADS, PLATES, ELECTRICAL INTERFACES)

L = INDUCTANCE (LEADS, PLATES, ETC.)

R_P = PARALLEL RESISTANCE (LEAKAGE CURRENT, DIELECTRIC ABSORPTION, INSULATION RESISTANCE)

Figure 2. Typical Capacitor Equivalent Circuit

The ESR is a function of frequency and temperature. It arises from such sources as dielectric losses, resistance of connections and conductors, plate or foil resistance, i.e., both the R_P and R_S elements in the equivalent circuit.

The losses in a capacitor are represented by dissipation factor (DF) and power factor (PF). These factors are defined in terms of the loss angle, δ, which is the deviation in the phase angle between current and voltage from the ideal of 90 degrees, and are the result of the ESR. The power factor is a convenient means of describing the proportion of ESR to total impedance.

For purposes of this discussion capacitors will be classified in three main groups:

1 Rigid dielectric, including CMR, CKR, CYR, CCR, etc.

2 Film/paper, including CQR, CPV, CFR, CHR, etc.

3 Electrolytic, including aluminum and tantalum (CE, CU, CLR, CSR)

These groups divide the capacitors into similar dielectric types.

Capacitors of the rigid dielectric type are characterized by low power factor. This, together with relatively low capacitance compared to the other types, results in these capacitor types being voltage limited at lower frequencies rather than limited by internal heating. Although current is a limiting factor at very high frequencies for these devices, they are not discussed further in regard to ripple effects. The present treatment of these rigid dielectric types in the Handbook seems complete and requires no additional factors or methods to account for ac voltage.

Capacitors of the other two types, the electrolytic and film/paper groups, exhibit significant temperature rise due to ripple current at much lower frequencies. Methods for determining the temperature rise for these two capacitor types were investigated.

The existing methods for handling ripple effects in MIL-HDBK-217B and possible improvements to those methods are addressed in section 3.2.4.3.2, followed by discussion of a new approach investigated for determining the effects of ripple.

3.2.4.3.2 Methods for Calculation

Effective Temperature Method (MIL-HDBK-217B)

The effect of ripple on capacitor reliability is presently accounted for in MIL-HDBK-217 two ways. First, the ripple voltage is included with the voltage used to determine S, the measure of electrical stress. Additionally, for some capacitor styles (CQ, CQR, CHR, CFV), the ripple voltage is used to determine a Δt temperature rise. This rise is caused by internal heating and is added to the ambient temperature to arrive at an effective temperature. This effective temperature is then used in determining λ_b, the base failure rate for the capacitor. The only capacitor types for which this Δt method is presently included are the film/paper types.

Two figures in MIL-HDBK-217B refer to ripple effects on temperature. These figures are reproduced herein as Figures 3 and 4.

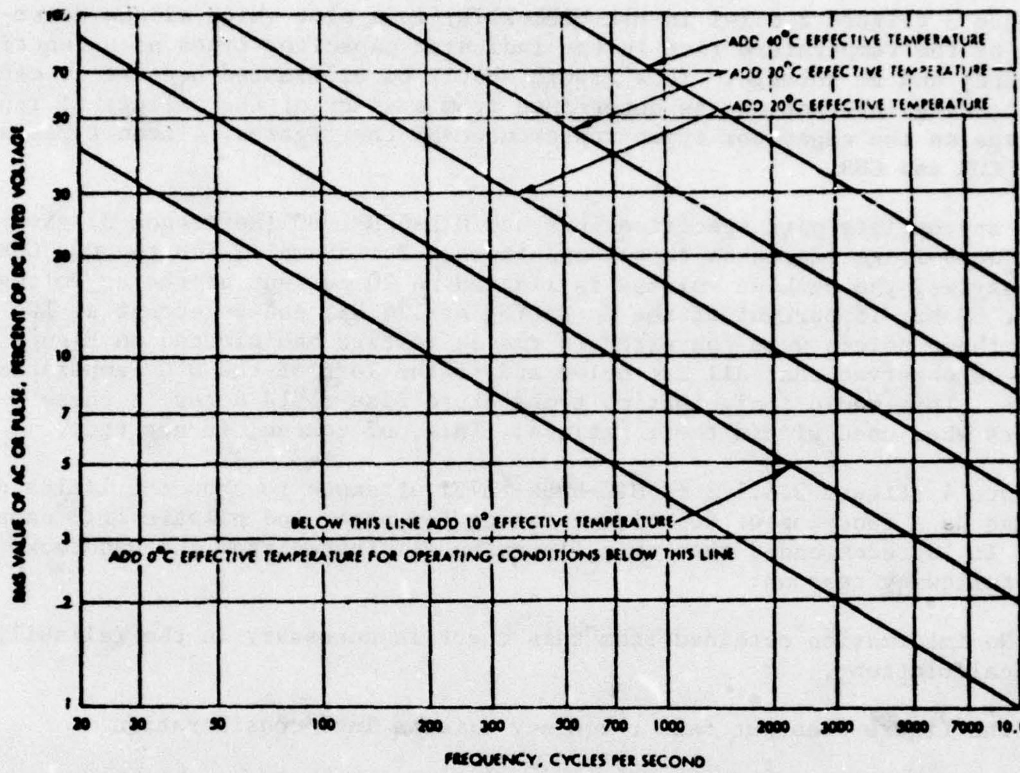


Figure 3. Equivalent Temperature Increase for Effects of AC or Pulses for Paper and Plastic Film Capacitors (Applicable to MIL-C-14157 and MIL-C-19978, Chars. E, K, M and Q; MIL-C-39022 all styles)

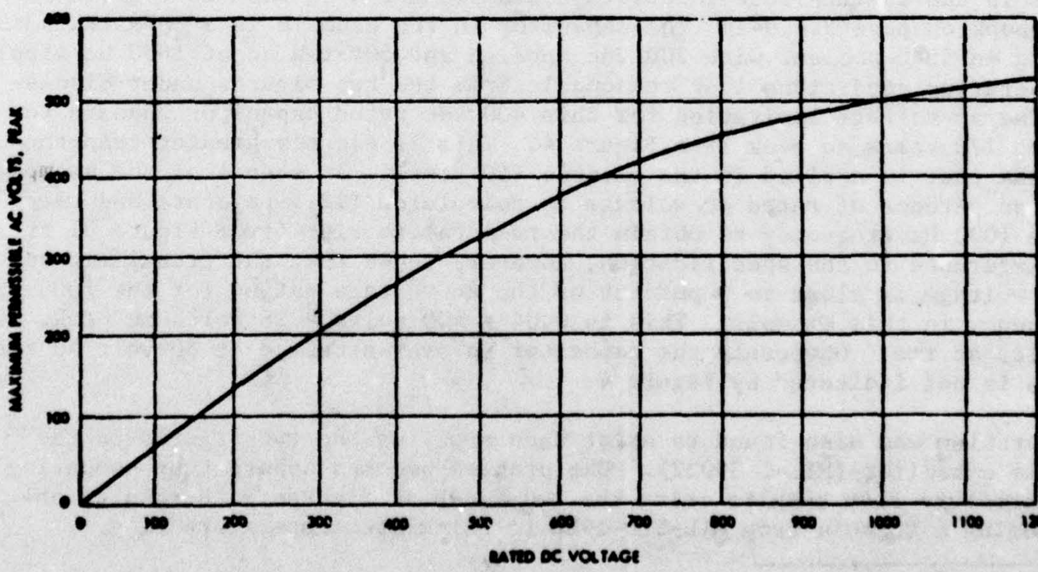


Figure 4. Basic Restriction on Use of Paper and Plastic Film Capacitors in AC Applications (Applicable only to MIL-C-14157 and MIL-C-19978, Chars. E, K, M and Q; MIL-C-39022 all styles)

Figure 3 (Figure 2.6.1-1 in MIL-HDBK-217B) is a plot which allows determination of the temperature rise in the indicated capacitor types as a function of frequency and ac voltage. This figure should be eliminated because it can give misleading information, as determined from a study of the effects of ripple voltage on the capacitor types represented by the figures. These types are CPV, CQ, CQR and CHR.

The appropriate part specifications and MIL-STD-198C (Reference 8) give specific ac voltage limits on these capacitors. For example, for the CQ, CQR, and CPV styles, the peak ac voltage is limited to 20 percent of the dc voltage rating at 60 Hz, 15 percent of the dc rating at 120 Hz, and 1 percent at 10 kHz. If these points were converted to rms ac voltage and plotted on Figure 3, it would be observed that all are below and to the left of the 0°C temperature rise line. This would imply that no temperature rise could occur in these capacitors when used within their ratings. This, of course, is not true.

Figure 4 (Figure 2.6.1-2 in MIL-HDBK-217B) attempts to show the limits on ac voltage as a function of dc voltage rating for paper and plastic film capacitors. It is recommended that this figure be eliminated from the Handbook for the following reasons:

1 No information obtained from this chart is necessary in the reliability calculation

2 The figure does not take frequency effects into consideration

3 The limits shown on the figure do not reflect the actual limitations of the capacitor types represented.

The problems arising from the two figures taken from the Handbook are apparent in the failure rate calculation example for a CQ capacitor given in the Handbook on page 2.6.9-1. The capacitor in the example is a CQ09A1KE153K3, operating in 55°C ambient with 200 Vdc applied and 50V rms ac at 1000 Hz ripple. These operating conditions look reasonable from the two figures under discussion. The ac voltage limitation for this 400 Vdc rated capacitor appears to be around 270 volts ac peak from Figure 4. This is clearly greater than the 70.7V peak that is applied in the example (50 Vrms). In step 4 of the example, the rms ac percent of rated dc voltage is calculated (12.5 percent) and used with the 1000 Hz frequency to obtain the temperature rise (from Figure 3) of 20°C. Reference to the specification, however, shows that the true limit on peak ac voltage is close to 4 percent of the dc voltage rating for the 1000 Hz ac frequency in this example. This is 0.04 x 400 volts = 16 volts ac peak, or 11.3 volts ac rms. Obviously the capacitor is over-stressed at 50 volt ac rms, but this is not indicated by Figure 4.

A problem was also found to exist when applying the two figures to the CHR style capacitor (MIL-C-39022). The problem becomes apparent by comparing the temperature rise results using the two Handbook figures with results obtained using a formula from MIL-STD-198C to calculate temperature rise.

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8. "Military Standard Capacitors, Selection and Use of," MIL-STD-198C, U.S. Army Electronics Command, 16 August 1974.

Effective Temperature Method (MIL-STD-198)

In MIL-STD-198C the limit of ac voltage that can be applied to CHR style capacitors is given by a formula involving the frequency, ambient temperature, and physical capacitor characteristics including capacitance and case area. This is given as:

$$V_P = \sqrt{\frac{\left(T_{dc} - T\right) Ae}{\pi fCD}}$$

where:

V_P is the maximum peak ac voltage

T_{dc} is the maximum rated temperature

A is the area of the case

f is the frequency

C is the capacitance

e and D are treated as constants for convection coefficient and dissipation factor (D is not a constant in the true sense, but its variations are small compared to the effects of C, f, and A).

A further limitation is that the ac peak voltage must not exceed 20 percent of the rated dc voltage, but the first limit is the one related to temperature rise effects of ripple. The (T_{dc} - T) factor is the difference between ambient and maximum temperature and can be interpreted as the allowable ΔT due to ac voltage application. The equation can be solved for this ΔT giving:

$$\Delta T = \frac{{V_P}^2 \pi fCD}{Ae}$$

or

$$\Delta T = \left(V_P\right)^2 \ (f) \left(\frac{C}{A}\right) \left(\frac{\pi D}{e}\right)$$

which shows that the temperature rise is proportional to the square of the ac voltage applied, the frequency, and C/A which is the ratio of capacitance to case area for the particular capacitor. $\pi D/e$ is a constant term, so ΔT is a function of V_P, f, and C/A.

When the results obtained by using this formula for calculating ΔT are compared to the results obtained by using the two figures in MIL-HDBK-217B, the problem associated with the Handbook figures are evident. This can be illustrated by an example where temperature rise is calculated for two CHR19 capacitors with the same dc voltage rating (200 Vdc), but with different case

sizes and capacitance values. Calculating the C/A of the first capacitor which has a capacitance of 0.1 μF:

$$\frac{C}{A} = \frac{0.1}{\pi(1.125)(0.312)} = 0.09\ \mu F/in^2.$$

Similarly, the C/A value for the other capacitor which has a capacitance of 8.2 μF is:

$$\frac{C}{A} = \frac{8.2}{\pi(2.625)(1)} = 1.0\ \mu F/in^2.$$

Since ΔT is proportional to the C/A factor and there is a greater than 10:1 difference in C/A for the two capacitors, then if both capacitors are applied with the same ripple voltage and frequency, the 8.2 μF capacitor will have more than 10 times the temperature rise of the 0.1 μF capacitor. If the ΔT is determined by using the curves shown in Figures 3 and 4 (taken from MIL-HDBK-217B), the temperature rise for the two capacitors would be equal.

The method using the formula for ΔT, then, gives much more meaningful results than the figures in the Handbook at present, but requires the inclusion of much more data from the specification slash sheets.

For a particular C/A, it would be possible to plot ΔT against V_P and obtain a family of curves, wherein the different curves represent different frequencies. But C/A varies greatly, even within part type. For example, C/A variations on the order of 100:1 can be found in the CHR part type. This would imply the necessity of a great number of the ΔT versus V_P families for the different C/A values.

A more reasonable approach than the inclusion of so many curve families would be to use the formula for ΔT. For the CHR capacitor style, this would necessitate the inclusion in the Handbook of tables of C/A values for each capacitor covered by each slash sheet in the specification, or would require a reference to the specification to determine the value of A, which would have to be calculated from length and diameter data given in the slash sheets and converted to the desired units.

From a study of the literature, consultation with components experts, and discussions with manufacturers, it is believed that the same formula can be applied to other capacitor types of similar construction. These include the CQ/CQR and CPV styles which are currently included in the MIL-HDBK-217B Figures 2.6.1-1 and 2.6.1-2. This is due to the similarity in constants for dissipation factor and the mechanisms through which internal heat is conducted through the foils or metallized film to the case and carried away by convection. This would mean the inclusion of still more pages of area data for these capacitor types.

The possibility of including the data for film/paper capacitors necessary for ΔT calculations was examined and found to be impractical. To illustrate the impracticality of this approach, the information required from only one slash sheet of MIL-C-39022(/5) to perform the ΔT calculations is shown in Table 32. Similar information from all other slash sheets would have to be deter-

mined and the same process would have to be performed for each other capacitor style using this method for calculating ΔT.
Similarly, the C/A value for the other capacitor which has a capacitance of 8.2 μF is:

$$\frac{C}{A} = \frac{8.2}{\pi(2.625)(1)} = 1.0\ \mu F/in^2.$$

Since ΔT is proportional to the C/A factor and there is a greater than 10:1 difference in C/A for the two capacitors, then if both capacitors are applied with the same ripple voltage and frequency, the 8.2 μF capacitor will have more than 10 times the temperature rise of the 0.1 μF capacitor. If the ΔT is determined by using the curves shown in Figures 3 and 4 (taken from MIL-HDBK-217B), the temperature rise for the two capacitors would be equal.

The method using the formula for ΔT, then, gives much more meaningful results than the figures in the Handbook at present, but requires the inclusion of much more data from the specification slash sheets.

For a particular C/A, it would be possible to plot ΔT against V_p and obtain a family of curves, wherein the different curves represent different frequencies. But C/A varies greatly, even within part type. For example, C/A variations on the order of 100:1 can be found in the CHR part type. This would imply the necessity of a great number of the ΔT versus V_p families for the different C/A values.

An alternate approach to the inclusion of so many curve families would be to use the formula for ΔT. From a study of the literature, consultation with components experts, and discussions with manufacturers, it is believed that the same formula can be applied to other capacitor types of similar construction. These include the CQ/CQR and CPV styles which are currently included in the MIL-HDBK-217B Figures 2.6.1-1 and 2.6.1-2. This is due to the similarity in constants for dissipation factor and the mechanisms through which internal heat is conducted through the foils or metallized film to the case and carried away by convection.

For the CHR capacitor style, use of the formula would necessitate the inclusion in the Handbook of tables of C/A values for each capacitor covered by each slash sheet in the specification, or would require a reference to the specification to determine the value of A, which would have to be calculated from length and diameter data given in the slash sheets and converted to the desired units.

The possibility of including in MIL-HDBK-217B the data for CHR style as well as other film/paper capacitors necessary for ΔT calculations was examined and found to be impractical. To illustrate the impracticality of this approach, the information required from only one slash sheet of the CHR style (MIL-C-39022/5) to perform the ΔT calculations is shown in Table 32. Similar information from all other slash sheets would have to be determined and the same process would have to be performed for each other capacitor style using this method for calculating ΔT.

TABLE 32

Data Required to Calculate Ripple Heat Rise for MIL-C-39022/5 (CHR59)

Capacitance (μF)	DC Rated Voltage	Ckt Diagram	Area (cm^2)	$\frac{\pi CD}{Ae}$
0.010	200	1	2.66	3.93×10^{-5}
0.010	200	3	2.44	4.29×10^{-5}
0.012	200	1	2.96	4.24×10^{-5}
0.012	200	3	2.72	4.62×10^{-5}
0.015	200	1	2.96	5.30×10^{-5}
0.015	200	3	2.72	5.78×10^{-5}
0.018	200	1	3.57	5.27×10^{-5}
0.018	200	3	3.28	5.75×10^{-5}
0.022	200	1	3.57	6.45×10^{-5}
0.022	200	3	3.28	7.03×10^{-5}
0.027	200	1	3.57	7.91×10^{-5}
0.027	200	3	3.28	8.63×10^{-5}
0.033	200	1	3.57	9.67×10^{-5}
0.033	200	3	3.28	1.05×10^{-4}
0.039	200	1	5.53	7.39×10^{-5}
0.039	200	3	5.13	7.95×10^{-5}
0.047	200	1	5.53	8.91×10^{-5}
0.047	200	3	5.13	9.59×10^{-5}
0.056	200	1	5.53	1.06×10^{-4}
0.056	200	3	5.13	1.14×10^{-4}
0.068	200	1	5.53	1.29×10^{-4}
0.068	200	3	5.13	1.39×10^{-4}
0.082	200	1	5.53	1.55×10^{-4}
0.082	200	3	5.13	1.67×10^{-4}
0.10	200	1	5.53	1.89×10^{-4}
0.10	200	3	5.13	2.04×10^{-4}
0.12	200	1	7.11	1.77×10^{-4}
0.12	200	3	6.72	1.87×10^{-4}

TABLE 32 (Cont)

Capacitance (μF)	DC Rated Voltage	Ckt Diagram	Area (cm^2)	$\frac{\pi CD}{Ae}$
0.15	200	1	7.11	2.21×10^{-4}
0.15	200	3	6.72	2.34×10^{-4}
0.18	200	1	7.09	2.66×10^{-4}
0.18	200	3	6.58	2.86×10^{-4}
0.22	200	1	7.09	3.25×10^{-4}
0.22	200	3	6.58	3.50×10^{-4}
0.27	200	1	9.11	3.10×10^{-4}
0.27	200	3	8.61	3.28×10^{-4}
0.33	200	1	9.11	3.79×10^{-4}
0.33	200	3	8.61	4.01×10^{-4}
0.39	200	1	11.1	3.67×10^{-4}
0.39	200	3	10.6	3.84×10^{-4}
0.47	200	1	11.1	4.42×10^{-4}
0.47	200	3	10.6	4.63×10^{-4}
0.56	200	1	12.8	4.58×10^{-4}
0.56	200	3	12.1	4.85×10^{-4}
0.68	200	1	12.8	5.56×10^{-4}
0.68	200	3	12.1	5.89×10^{-4}
0.82	200	1	15.7	5.49×10^{-4}
0.82	200	3	14.9	5.75×10^{-4}
1.0	200	1	15.7	6.69×10^{-4}
1.0	200	3	14.9	7.01×10^{-4}
2.0	200	1	22.1	9.50×10^{-4}
2.0	200	3	21.2	9.87×10^{-4}
2.5	200	1	25.4	1.03×10^{-3}
2.5	200	3	24.6	1.06×10^{-3}
3.0	200	1	28.5	1.10×10^{-3}
3.0	200	3	27.5	1.14×10^{-3}
4.0	200	1	32.3	1.30×10^{-3}
4.0	200	3	31.3	1.34×10^{-3}

TABLE 32 (Cont)

Capacitance (μF)	DC Rated Voltage	Ckt Diagram	Area (cm^2)	$\frac{\pi CD}{Ae}$
5.0	200	1	36.1	1.45×10^{-3}
5.0	200	3	35.1	1.49×10^{-3}
7.0	200	1	38.0	1.93×10^{-3}
7.0	200	3	36.7	2.00×10^{-3}
8.0	200	1	43.0	1.95×10^{-3}
8.0	200	3	41.8	2.00×10^{-3}
9.0	200	1	48.1	1.96×10^{-3}
9.0	200	3	46.9	2.01×10^{-3}
10.0	200	1	53.2	1.97×10^{-3}
10.0	200	3	51.9	2.02×10^{-3}
0.010	400	1	5.53	1.89×10^{-5}
0.010	400	3	5.13	2.04×10^{-5}
0.012	400	1	5.53	2.27×10^{-5}
0.012	400	3	5.13	2.45×10^{-5}
0.015	400	1	5.53	2.84×10^{-5}
0.015	400	3	5.13	3.06×10^{-5}
0.018	400	1	5.53	3.41×10^{-5}
0.018	400	3	5.13	3.67×10^{-5}
0.022	400	1	5.53	4.17×10^{-5}
0.022	400	3	5.13	4.49×10^{-5}
0.027	400	1	7.11	3.98×10^{-5}
0.027	400	3	6.72	4.21×10^{-5}
0.033	400	1	7.11	4.86×10^{-5}
0.033	400	3	6.72	5.15×10^{-5}
0.039	400	1	7.11	5.75×10^{-5}
0.039	400	3	6.72	6.08×10^{-5}
0.047	400	1	7.11	6.92×10^{-5}
0.047	400	3	6.72	7.33×10^{-5}
0.056	400	1	9.11	6.44×10^{-5}
0.056	400	3	8.61	6.81×10^{-5}

TABLE 32 (Cont)

Capacitance (μF)	DC Rated Voltage	Ckt Diagram	Area (cm^2)	$\frac{\pi CD}{Ae}$
0.068	400	1	9.11	7.81×10^{-5}
0.068	400	3	8.61	8.27×10^{-5}
0.082	400	1	11.14	7.71×10^{-5}
0.082	400	3	10.6	8.07×10^{-5}
0.10	400	1	11.14	9.40×10^{-5}
0.10	400	3	10.6	9.85×10^{-5}
0.12	400	1	11.4	1.10×10^{-4}
0.12	400	3	10.8	1.17×10^{-4}
0.15	400	1	11.4	1.38×10^{-4}
0.15	400	3	10.8	1.46×10^{-4}
0.18	400	1	15.7	1.20×10^{-4}
0.18	400	3	14.9	1.26×10^{-4}
0.22	400	1	15.7	1.47×10^{-4}
0.22	400	3	14.9	1.54×10^{-4}
0.27	400	1	18.5	1.53×10^{-4}
0.27	400	3	17.8	1.58×10^{-4}
0.33	400	1	18.5	1.87×10^{-4}
0.33	400	3	17.8	1.94×10^{-4}
0.39	400	1	22.1	1.85×10^{-4}
0.39	400	3	21.2	1.92×10^{-4}
0.47	400	1	22.1	2.23×10^{-4}
0.47	400	3	21.2	2.32×10^{-4}
0.56	400	1	25.4	2.30×10^{-4}
0.56	400	3	24.6	2.38×10^{-4}
0.68	400	1	25.4	2.80×10^{-4}
0.68	400	3	24.6	2.89×10^{-4}
0.82	400	1	32.3	2.66×10^{-4}
0.82	400	3	31.3	2.74×10^{-4}
1.0	400	1	32.3	3.24×10^{-4}
1.0	400	3	31.3	3.34×10^{-4}

TABLE 32 (Cont)

Capacitance (μF)	DC Rated Voltage	Ckt Diagram	Area (cm^2)	$\frac{\pi CD}{Ae}$
2.0	400	1	43.0	4.87×10^{-4}
2.0	400	3	41.8	5.01×10^{-4}
2.5	400	1	53.2	4.92×10^{-4}
2.5	400	3	51.9	5.04×10^{-4}
0.010	600	1	5.53	1.89×10^{-5}
0.010	600	3	5.13	2.04×10^{-5}
0.012	600	1	9.11	1.38×10^{-5}
0.012	600	3	8.61	1.46×10^{-5}
0.015	600	1	9.11	1.72×10^{-5}
0.015	600	3	8.61	1.82×10^{-5}
0.018	600	1	9.11	2.07×10^{-5}
0.018	600	3	8.61	2.19×10^{-5}
0.022	600	1	9.11	2.53×10^{-5}
0.022	600	3	8.61	2.68×10^{-5}
0.027	600	1	9.11	3.10×10^{-5}
0.027	600	3	8.61	3.28×10^{-5}
0.033	600	1	9.11	3.79×10^{-5}
0.033	600	3	8.61	4.01×10^{-5}
0.039	600	1	11.1	3.67×10^{-5}
0.039	600	3	10.6	3.84×10^{-5}
0.047	600	1	11.1	4.42×10^{-5}
0.047	600	3	10.6	4.63×10^{-5}
0.056	600	1	12.8	4.58×10^{-5}
0.056	600	3	12.1	4.85×10^{-5}
0.068	600	1	12.8	5.56×10^{-5}
0.068	600	3	12.1	5.89×10^{-5}
0.082	600	1	15.7	5.49×10^{-5}
0.082	600	3	14.9	5.75×10^{-5}
0.10	600	1	15.7	6.69×10^{-5}
0.10	600	3	14.9	7.01×10^{-5}

TABLE 32 (Cont)

Capacitance (μF)	DC Rated Voltage	Ckt Diagram	Area (cm^2)	$\frac{\pi CD}{Ae}$
0.12	600	1	18.5	6.79×10^{-5}
0.12	600	3	17.8	7.06×10^{-5}
0.15	600	1	18.5	8.49×10^{-5}
0.15	600	3	17.8	8.83×10^{-5}
0.18	600	1	22.1	8.55×10^{-5}
0.18	600	3	21.2	8.89×10^{-5}
0.22	600	1	22.1	1.04×10^{-4}
0.22	600	3	21.2	1.09×10^{-4}
0.27	600	1	28.5	9.93×10^{-5}
0.27	600	3	27.5	1.02×10^{-4}
0.33	600	1	28.5	1.21×10^{-4}
0.33	600	3	27.5	1.25×10^{-4}
0.39	600	1	36.1	1.13×10^{-4}
0.39	600	3	35.1	1.16×10^{-4}
0.47	600	1	36.1	1.36×10^{-4}
0.47	600	3	35.1	1.40×10^{-4}
0.56	600	1	38.0	1.54×10^{-4}
0.56	600	3	36.7	1.60×10^{-4}
0.68	600	1	38.0	1.87×10^{-4}
0.68	600	3	36.7	1.94×10^{-4}
0.82	600	1	48.1	1.78×10^{-4}
0.82	600	3	46.9	1.83×10^{-4}
1.0	600	1	48.1	2.18×10^{-4}
1.0	600	3	46.9	2.23×10^{-4}

The electrolytics, another group of capacitors that has not been considered in terms of calculating effective temperature due to ripple, include the aluminum (CE and CU) and tantalum (CSR and CLR) styles. The ripple guidelines are quite detailed in the specifications, but an important observation on these limits is that they are application guidelines to ensure that the parts are applied within safe operating limits. These limits are determined differently for the different styles of capacitors. There are generally two types of electrolytic capacitors, the foil types (aluminum foil, tantalum foil, dry

aluminums) with either etched or plain foil, and the pellet (sintered anode) types. The pellet type capacitors are not specified for use in ac applications, even though some small signals may be imposed on the dc voltage. Published application guidelines give rules for voltage reversal on the pellet types, but the difference in stress due to the allowable ripple in an application and the stress due to pure dc alone is minute.

Specific rules are given in the application guidelines that impose current and voltage limitations on electrolytic capacitors. These limitations vary with case size, dielectric type, voltage rating, capacitance, temperature, frequency, etc. Due to the many variables involved, the inclusion of all necessary information in the Handbook would be undesirable. Also, the limitations on ac voltage and/or ripple current are given to ensure reliable operation. Included under those limitations are many combinations of variables in manufacturing processes and design that would render inaccurate any attempt to relate temperature rise resulting from ripple current to those limits. However, this is the only method found available to develop such a relation without extensive laboratory testing. The relation arrived at would be considerably more complex than that determined for the film types because the dissipation factor of the film types is much less dependent on frequency and temperature than the dissipation factor for electrolytics.

Effective Electrical Stress Method (New Concept)

Because of the above problems with the effective temperature method, (i.e., ambient $+\Delta T$), a second approach to including ripple effects in the failure rate model was sought. This second approach includes the effects of ripple as an input to the electrical stress, S, used in calculating the base failure rate. The manufacturers and the specifications give information on limits to ac voltage under varying conditions which are based on the design and construction of each particular capacitor type. The specification for CQR capacitors (MIL-C-19978), for example, specifies permissible ac voltage limits as a percent of dc voltage rating and frequency. The dc voltage rating and the specified ac limits already take into account the physical construction and those exact characteristics that were found so difficult to represent adequately in a single method for including ripple effects on temperature. These limitations on ac voltage become part of the electrical specification of the part type just as does dc voltage rating.

Including these ac limits as a factor into the calculation for electrical stress, S, the new calculation for S would be of the form:

$$S = \frac{Vdc(op)}{Vdc(rated)} + \left(1 - \frac{Vdc(op)}{Vdc(rated)}\right) \frac{Vac(op)}{Vac(rated)}$$

where

Vdc(op) is the dc component of voltage in the application

Vdc(rated) is the capacitor rating

Vac(op) is the ac component of the operating voltage (rms or peak)

Vac(rated) is the maximum ac voltage (measured in the same units as Vac(op) at the existing operating conditions as determined by the specification.

In particular, Vac(rated) takes into account the effects of frequency, temperature, dc voltage rating, and any other factors which apply to this particular capacitor in exactly the manner in which these factors influence the ac voltage limit.

This method for calculating S allocates a portion of the electrical stress to dc voltage. This portion is the term Vdc(op)/Vdc(rated) which can assume values from 0 to 1. The second term is composed of two factors. The first, 1 - Vdc(op)/Vdc(rated), is such that, when multiplied by the ac voltage stress, Vac(op)/Vac(rated) will allow the stress to increase up to a maximum of 1.0. This stress of 1.0 would occur any time the capacitor was operated at 100 percent of its ac limit. With no ac voltage applied, the value of S is exactly as it was in the original method.

This new method for handling ripple effects has several benefits. One benefit is that the temperature used in calculating the failure rate remains the ambient temperature. Another benefit is the wider applicability of this method to those part types that have no convenient way of calculating the ΔT from internal heating, but do have quite specific ratings for ac limits. Finally, this method accounts for the dependence of ripple effects on all pertinent variables, since the Vac(rated) term is determined from the specification and application guidelines that are specific to the part type

This second method has several questionable aspects, however, just as there were to the ΔT method. An "effective stress" term has been calculated which may or may not accurately reflect the failure rate effects in the proper proportion. Secondly, there are capacitor types (such as the CE style) which give ripple current limits as opposed to ripple voltage limits. Finally, this method would require the inclusion of large amounts of rating information from the specifications into the Handbook or refer the user to the specifications and/or MIL-STD-198C to obtain the ac limit for a particular application.

3.2.4.3.3 Results of Ripple Current Investigation

The large variety of capacitor styles covered by the Handbook and the wide variation in factors influencing ac limitations of these capacitors preclude the development of any simple method for handling ripple effects. The many variables and the extent to which each has an influence on internal heating even within a single specification require further investigation including laboratory testing to develop an adequate method. Therefore, because of the complexities involved with determining the effects of ripple

current, it is recommended that temperature rise be cálculated by using the methodology and data in MIL-STD-198 and the individual part specifications. Thus, no method has been included in the revision to MIL-HDBK-217B.

3.3 Inductive Devices Analysis Results

3.3.1 Transformer Model Revisions

Approximately 1.4 billion part hours of data were analyzed in five different environments: ground benign (G_B), ground fixed (G_F), naval sheltered (N_S), ground mobile (G_M), and subsonic airborne inhabited (A_{IT}). Table 33 lists the three transformer specifications included in this study. One specification, MIL-T-55631, is not in MIL-HDBK-217B. Inductors covered by MIL-T-27 are included with transformers.

TABLE 33

Transformer Specifications to be Included in Revision to MIL-HDBK-217B

Specification	Style	Description
MIL-T-27	TF	Audio, Power, and High Power Pulse
MIL-T-21038	TP	Low Power Pulse
MIL-T-55631	-	IF, RF, and Discriminator

The general failure rate model for inductive devices has been expanded by adding a construction factor to identify fixed or variable coils. All transformers covered by this study are fixed. The general model is:

$$\lambda_p = \lambda_b \, (\pi_E \times \pi_Q \times \pi_c)$$

where:

λ_p = Total failure rate in failures/10^6 hours

λ_b = Base failure rate

π_E = Environmental factor

π_Q = Quality factor

π_c = Construction factor (fixed or variable).

Almost without exception, the observed transformer failure rates were higher than the corresponding predicted values obtained from MIL-HDBK-217B. It was determined from the analysis that all transformer base failure rates in the Handbook should be increased by a factor of 2.5. This change was applied to the "A" constant in the general model for the base failure rate:

$$\lambda_b = A\, e^{x}$$

where

$$x = \left(\frac{T_{HS} + 273}{N_T}\right)^{G}$$

T_{HS} = Hot spot temperature in degrees centigrade

N_T = Temperature constant

G = Acceleration constant

A = Adjustment factor for different insulation classes.

The revised values for the "A" constant are shown in Table 34, along with the values for the G and N_T constants. The table also gives each specification insulation class code for the corresponding maximum rated operating temperature. The maximum temperature for class B insulation of MIL-T-55631 is 125°C; however, it has been grouped with the class "S" *insulation of* the other transformer types since the temperatures are so close.

TABLE 34

Transformer Base Failure Rate Model Constants versus Insulation Class

Specification	Insulation Class					
MIL-T-27	Q	R	S	V	T	U
MIL-T-21038	Q	R	S	T	U	V
MIL-T-55631	O	A	B	C	-	-
Model Constants	**Maximum Operating Temperature**					
	85°C	105°C	130°C	155°C	170°C	>170°C
A	1.59×10^{-3}	1.8×10^{-3}	1.52×10^{-3}	4.58×10^{-3}	5.08×10^{-3}	6.5×10^{-3}
N_T	329	352	364	409	398	477
G	15.6	14.0	8.7	10.0	3.8	8.4

Three environmental factors changed as a result of the data analysis and are included in Table 35. The subsonic airborne inhabited (A_{IT}) factor was increased to 15 from the value of 5 in MIL-HDBK-217B. (Although the Handbook does not delineate between subsonic and supersonic, the airborne values in it were considered subsonic for purposes of comparison.) The airborne environment was expanded from 2 to 4 factors to differentiate between subsonic and supersonic. The values for the supersonic factors were determined in the same manner as was done for resistors and capacitors.

TABLE 35

Revised Environmental Factors
for Inductive Devices

Category	Environmental Factor
G_B and S_F	1
G_F	2
G_M	12
A_{IT}	15
A_{IF}	30
N_S	4
N_U	12
A_{UT}	20
A_{UF}	40
M_L	30

The ground mobile (G_M) factor was increased from the Handbook value of 3 to 12 as a result of the data analysis. The Handbook presently has only a general naval factor rather than delineating between sheltered (N_S) and unsheltered (N_U). The data collected in the N_S environment indicated a factor of 4. To be consistent with other sections of the Handbook, an N_U factor was added and given the same value as that of the G_M environment. The subsonic airborne uninhabited (A_{UT}) factor and the missile launch (M_L) factor were increased to make them realistic with respect to the revised A_{IT} factor.

Only one change was made to the quality constant, π_Q. In the power transformer family the value for the lower quality grade was increased to 30 from the present value of 20. However, the upper grade will be deleted from the table because of a lack of a concrete definition for this grade.

3.3.2 RF Coil Model Revision

More than three billion part hours of field operating data on RF coils were collected and analyzed. The analysis encompassed four environments: airborne inhabited (subsonic), ground fixed, naval sheltered, and satellite. One of the two specifications covering coils, MIL-C-39010, will be a new addition to the Handbook. The two specifications are listed in Table 36.

TABLE 36

Coil Specifications to be Included in MIL-HDBK-217B Revision

Specification	Description
MIL-C-15305	Coils, Fixed and Variable, RF
MIL-C-39010	Coils, Molded, RF, ER

The general failure rate model was given in the transformer discussion, section 3.3.1. The new construction factor in the model was added to account for the variable coils included in MIL-C-15305. The factor will have a value of 1 for fixed coils and transformers and a value of 2 for variable coils. The base failure rate model remains the same as that given for transformers.

In contrast to the analysis results of the transformer data, the observed RF coil failure rates were significantly lower than the corresponding predicted values. Since the data indicated a difference between the transformer and coil failure rates, a separate base failure rate table will be constructed for RF coils in the Handbook revision. Although the base failure rate model remains the same as that for transformers, the Handbook value for the adjustment factor, A, will be reduced by a factor of 1.9. The values for the base failure rate constants for coils are given in Table 37, along with the insulation class codes for both specifications.

The environmental factors for coils will be the same as those for transformers, which are given in Table 35. However, the quality constants for RF coils will be separated from those for RF transformers. The quality level values for RF coils are given in Table 38. Since MIL-C-39010 is an established reliability specification, the factors for the quality levels covered by this specification have been included. The Military Standard and lower levels have been retained, but the values have been reduced as a result of the lower observed failure rates. The major difference between the established reliability specification, MIL-C-39010, and MIL-C-15305 were 100 percent inspection of parts in MIL-C-39010 Group A tests for thermal shock, inductance, and Q. Also, a 10,000 hour extended life test is performed monthly during MIL-C-39010 Group C testing. MIL-C-15305 group inspection tests are all sampling tests and the Group C life test consists of a semi-annual 2000 hour test.

TABLE 37

Coil Base Failure Rate Model Constants versus Insulation Class

Specification	Insulation Class			
MIL-C-15305	0	A	B	C
MIL-C-39010	-	A	B	F
Model Constants	Maximum Operating Temperature			
	85°C	105°C	125°C	150°C
A	3.35×10^{-4}	3.79×10^{-4}	3.19×10^{-4}	9.63×10^{-4}
N_T	329	352	364	409
G	15.6	14.0	8.7	10.0

TABLE 38

Revised RF Coil Quality Factor, π_Q

Failure Rate Level	π_f Factor
S	0.03
R	0.1
P	0.3
M	1.0
MIL-C-15305	4.0
Lower	20.0

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The revised base failure rates and modifying factors resulting from this study program are indicative of actual field experience on parts produced with state-of-the-art manufacturing techniques and should result in more realistic reliability predictions.

No general trend for base failure rates, either up or down, encompassed all part types. Adjustments were made in both directions. However, changes were significant for some isolated cases. The greatest change in base failure rates was made to the non-wirewound variable resistor (MIL-R-22097, RJ style) where the Handbook value was decreased by a factor of 22. This change was not surprising since the Handbook failure rate for this part was not realistic when compared to those of other variable resistors. For example, the RJ style base failure rate was about 43 times higher than that for variable wirewound resistors (MIL-R-27208, RT style). For capacitors, the most significant change was made to the paper and paper-plastic devices (MIL-C-19978, MIL-C-14157, and MIL-C-39022) where the base failure rates were increased by approximately a factor of 10. Transformer base failure rates were increased by a factor of 2.5, while those of coils were decreased by a factor of 1.9.

The literature search was instrumental in providing data that indicated a significant difference in reliability of equipment in subsonic versus supersonic aircraft. In addition to this study's limited amount of field data that indicated a difference, reported studies by two other contractors also indicated higher supersonic failure rates. Therefore, the number of aircraft environmental factors was expanded from two to four to separate supersonic from other types of aircraft.

The environmental factors for the fixed ground environment were standardized to have a value no higher than 3 for any fixed component. This can be compared to the baseline factor of 1.0 used throughout the Handbook for the ground benign environment. The Handbook presently has ratios up to 10 to 1 between these two environments, but no justification could be found to support such a difference for any part type. In fact, all evidence indicated just the opposite. Most of the data collected on this study that were classified as being in a fixed ground environment were air-conditioned and would not be considered much more severe than ground benign. The literature search revealed that similar results were obtained in an independent study by another contractor.

The quantitative factor for the naval sheltered environment was decreased for most part types. The revised factors for this environment approach those for the fixed ground environment in many instances. This is not unreasonable since equipment in the naval sheltered environment is protected and many times shock mounted. One factor that may have had some impact upon the results is the inclusion of submarine data in the naval sheltered category. An attempt was made to create a separate submarine factor, but insufficient data were available to substantiate doing this.

After a literature search and direct contact with manufacturers and contractors, it was determined that capacitor reliability is affected by the part capacitance value. Higher capacitance devices fail more frequently. Therefore, an additional factor that varies as a function of the part capacitance value was included in the fixed capacitor failure rate models. Previously, only the glass capacitors had a capacitance factor.

A study of the effects of ripple current on case temperature of capacitors indicated that significant increases in part temperature could result. A concerted effort was made to develop a method which would be included in the Handbook to calculate heat rise caused by ripple current. This was not successful as the methods found appropriate for determining temperature rise were too complex for their inclusion in the Handbook to be practical. An extensive quantity of reference data and quantitative factor values would be required for each part type. For some part types, the values of certain constants required to perform the necessary calculations could not be found in the literature researched. The best way found to determine the effects of ripple current was to use the methods and data given in the individual part specifications and MIL-STD-198, "Capacitors, Selection and Use of."

An evaluation of the nonsolid tantalum capacitor specifications (MIL-C-3965 and MIL-C-39006) revealed significant variations in the construction and materials used in different styles of these capacitors. These variations have a definite impact upon reliability. Therefore, a construction factor was added to the failure rate model for these capacitors to improve the reliability prediction accuracy. The new factor delineates between slug and foil types, hermetic and nonhermetic cases, and separates the all-tantalum style from the others.

4.2 Recommendations

The following recommendations are submitted for consideration and possible implementation:

1 A separate study should be performed on the effects of ripple current on case temperature of capacitors. Such a study would require research on analytical methodology for predicting ripple current heat rise. Values such as convection coefficients and dissipation factor variation with temperature may have to be derived for many part types. Component testing should be performed to verify theoretical models developed by the study.

2 Additional studies should be performed to determine the relative differences between Established Reliability quality levels. The Handbook quality factors presently indicate a difference of about 33 to 1 between the S level and the M level. Although there was insufficient data collected during the study to draw definite conclusions, there were some indications that this difference may be closer to 10 to 1.

3 Detailed studies should be performed to determine the difference between submarine and shipboard sheltered environments. Data from these two environments were combined during this study because there was no statistical justification for separating them. This was a result of insufficient comparative data with which to perform a statistical test. Shipboard data is more difficult to obtain, as documentation of failures to the part level is not done as rigorously as on submarine systems.

4 Military data collection systems should be reevaluated such that more reliability-oriented information can be collected. These systems presently are useful for logistics and replacement data studies, but are difficult and sometimes impossible to use as a source for reliability data. In the defense of these data collection systems, it should be noted that one problem in collecting part-level data is the growing tendency to throw away failed modules rather than isolate and repair failed parts within them.

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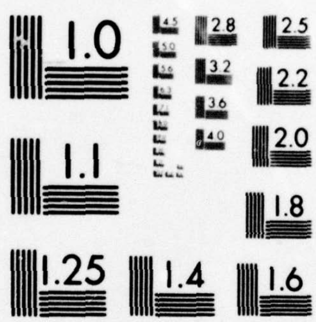

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APPENDIX A

SUMMARY OF DATA COLLECTED

TABLE A-1.

Resistor Operating Data Summary

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-R-11	RC	A_{IT}	MIL	-0-	118.802	0.0077
MIL-R-11	RC	G_F	MIL	111	23,444.400	0.0049
MIL-R-11	RC	G_M	MIL	-0-	0.903	1.013
MIL-R-11	RC	N_S	MIL	31	55,463.00	0.0006
MIL-R-19	RA	G_F	MIL	1	4.288	0.471
MIL-R-19	RA	N_S	MIL	1	5.360	0.377
MIL-R-22	RP	G_F	MIL	-0-	1.473	0.621
MIL-R-26	RW	A_{IT}	MIL	2	20.722	0.150
MIL-R-26	RW	G_F	MIL	437	5,312.680	0.083
MIL-R-26	RW	G_M	MIL	-0-	3.202	0.286
MIL-R-26	RW	N_S	MIL	5	638.178	0.0099
MIL-R-93	RB	G_F	MIL	-0-	11.601	0.079
MIL-R-93	RB	N_S	MIL	-0-	1,513.790	0.0006
MIL-R-94	RV	A_{IT}	MIL	-0-	0.005	-
MIL-R-94	RV	G_F	MIL	12	56.504	0.241
MIL-R-94	RV	G_M	MIL	3	2.035	2.052
MIL-R-94	RV	N_S	MIL	2	7.482	0.415

*All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-1. (Cont)

PART TYPE	ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-R-10509 RN	A_{IT}	MIL	1	257.014	0.0079
MIL-R-10509 RN	G_F	HIGHER	-0-	11.975	0.076
MIL-R-10509 RN	G_F	MIL	26	15,823.600	0.0018
MIL-R-10509 RN	G_M	MIL	-0-	10.743	0.085
MIL-R-10509 RN	N_S	MIL	13	17,492.900	0.00083
MIL-R-11804 RD	N_S	MIL	-0-	0.540	1.694
MIL-R-12934 RR	G_F	MIL	1	0.910	2.220
MIL-R-18546 RE	G_F	MIL	-0-	38.979	0.023
MIL-R-18546 RE	G_M	MIL	-0-	0.014	-
MIL-R-18546 RE	N_S	MIL	-0-	148.426	0.0062
MIL-R-22097 RJ	A_{IT}	MIL	-0-	2.934	0.312
MIL-R-22097 RJ	G_F	MIL	14	106.390	0.147
MIL-R-22097 RJ	G_M	MIL	-0-	0.968	0.945
MIL-R-22097 RJ	N_S	MIL	8	14.148	0.668
MIL-R-22684 RL	A_{IT}	MIL	-0-	1.917	0.474
MIL-R-22684 RL	G_F	MIL	2	10,540.500	0.00029
MIL-R-22684 RL	G_M	MIL	-0-	90.385	0.010

*All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-1. (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS (x 10^6)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-R-22684	RL	N_S	MIL	-0-	25.488	0.036
MIL-R-23285	RVC	G_B	MIL	-0-	0.755	1.212
MIL-R-27208	RT	A_{IT}	MIL	-0-	5.919	0.155
MIL-R-27208	RT	G_F	MIL	3	79.230	0.053
MIL-R-27208	RT	G_M	MIL	-0-	0.076	-
MIL-R-27208	RT	N_S	MIL	180	1,234.796	0.149
MIL-R-39005	RBR	G_B	S	-0-	11,436.000	0.000080
MIL-R-39005	RBR	S_F	P	-0-	12.593	0.073
MIL-R-39005	RBR	N_S	M	-0-	47.380	0.019
MIL-R-39007	RWR	A_{IT}	M	-0-	20.353	0.045
MIL-R-39007	RWR	A_{IT}	P	-0-	0.026	-
MIL-R-39007	RWR	A_{UT}	M	-0-	0.011	-
MIL-R-39007	RWR	A_{UT}	R	-0-	9.168	0.100
MIL-R-39007	RWR	G_B	S	2	22,555.000	0.00014
MIL-R-39007	RWR	G_F	R	-0-	3.819	0.240
MIL-R-39007	RWR	G_M	M	-0-	0.028	-
MIL-R-39007	RWR	G_M	P	-0-	0.250	-
MIL-R-39007	RWR	G_M	R	-0-	0.374	-
MIL-R-39007	RWR	N_S	M	-0-	62.101	0.015

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-1. (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-R-39007	RWR	N_S	R	-0-	1.560	0.587
MIL-R-39007	RWR	S_F	M	-0-	23.387	0.039
MIL-R-39007	RWR	S_F	R	-0-	12.573	0.073
MIL-R-39008	RCR	A_{IT}	M	-0-	184.501	0.0050
MIL-R-39008	RCR	A_{IT}	P	-0-	2.116	0.432
MIL-R-39008	RCR	A_{IT}	S	-0-	0.038	-
MIL-R-39008	RCR	A_{UT}	L	-0-	0.104	-
MIL-R-39008	RCR	A_{UT}	S	-0-	125.628	0.0073
MIL-R-39008	RCR	G_F	M	-0-	66.427	0.014
MIL-R-39008	RCR	G_F	S	-0-	73.845	0.012
MIL-R-39008	RCR	G_M	M	-0-	3.247	0.282
MIL-R-39008	RCR	G_M	P	-0-	0.222	-
MIL-R-39008	RCR	G_M	S	-0-	26.746	0.034
MIL-R-39008	RCR	N_S	M	-0-	5,306.800	0.00017
MIL-R-39008	RCR	N_S	S	-0-	4,401.694	0.00021
MIL-R-39008	RCR	S_F	R	-0-	130.780	0.0070
MIL-R-39008	RCR	S_F	S	-0-	2,025.740	0.00045
MIL-R-39009	RER	A_{IT}	M	7	108.845	0.077
MIL-R-39009	RER	A_{IT}	P	-0-	0.094	-
MIL-R-39009	RER	G_F	M	-0-	0.007	-

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-1. (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS (x 10^6)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-R-39009	RER	G_F	R	-0-	0.419	-
MIL-R-39009	RER	G_M	M	-0-	0.378	-
MIL-R-39009	RER	N_S	M	-0-	0.274	-
MIL-R-39009	RER	N_S	R	-0-	0.174	-
MIL-R-39009	RER	S_F	R	-0-	0.054	-
MIL-R-39015	RTR	A_{IT}	M	-0-	7.600	0.120
MIL-R-39015	RTR	A_{IT}	P	-0-	0.041	-
MIL-R-39015	RTR	A_{UT}	M	-0-	0.002	-
MIL-R-39015	RTR	G_F	R	-0-	0.350	-
MIL-R-39015	RTR	G_M	M	-0-	0.642	1.425
MIL-R-39015	RTR	N_S	R	-0-	0.144	-
MIL-R-39015	RTR	N_S	M	1	0.922	2.191
MIL-R-39017	RLR	A_{UT}	M	-0-	0.058	-
MIL-R-39017	RLR	A_{UT}	R	-0-	5.976	0.153
MIL-R-39017	RLR	G_F	M	-0-	114.436	0.0080
MIL-R-39017	RLR	G_M	M	2	83.395	0.037
MIL-R-39017	RLR	G_M	P	-0-	1.846	0.496
MIL-R-39017	RLR	G_M	S	-0-	0.028	-
MIL-R-39017	RLR	N_S	M	1	8078.726	0.00025
MIL-R-39017	RLR	S_F	R	-0-	7.205	0.127

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-1. (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS (x 10^6)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-R-39035	RJR	A_{UT}	M	-0-	0.002	-
MIL-R-55182	RNR	A_{IT}	P	-0-	0.448	-
MIL-R-55182	RNR	A_{IT}	M	1	280.551	0.0072
MIL-R-55182	RNR	A_{IT}	S	-0-	0.443	-
MIL-R-55182	RNR	A_{UT}	M	-0-	0.045	-
MIL-R-55182	RNR	A_{UT}	R	-0-	75.936	0.012
MIL-R-55182	RNR	G_B	S	1	51,925.981	0.000039
MIL-R-55182	RNR	G_F	M	-0-	12.937	0.071
MIL-R-55182	RNR	G_F	S	-0-	29.210	0.031
MIL-R-55182	RNR	G_M	M	-0-	2.756	0.332
MIL-R-55182	RNR	G_M	P	-0-	0.014	-
MIL-R-55182	RNR	G_M	S	-0-	0.083	-
MIL-R-55182	RNR	G_M	R	-0-	11.256	0.081
MIL-R-55182	RNR	N_S	M	-0-	705.018	0.0013
MIL-R-55182	RNR	N_S	S	-0-	11.795	0.078
MIL-R-55182	RNR	S_F	R	-0-	2,273.466	0.00040
MIL-R-55182	RNR	S_F	S	-0-	615.008	0.0015

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-1. (Cont) BEST AVAILABLE COPY

PART TYPE	ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
NETWORK 12 Elements	G_F	MIL	4	217.275	0.024
THERMISTOR	G_F	MIL	-0-	0.250	-
THERMISTOR	G_F	MIL	-0-	4.800	0.191
THERMISTOR	G_M	MIL	-0-	0.021	-
THERMISTOR	S_F	MIL	1	9.118	0.222
TOTALS			873	243,613.572	

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-2

Capacitor Operating Data Summary

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS (x 10^6)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-C-5	CM	A_{IF}	MIL	1	0.011	-
MIL-C-5	CM	A_{IT}	MIL	9	26.223	0.400
MIL-C-5	CM	G_F	MIL	4	2165.580	0.0024
MIL-C-5	CM	G_M	MIL	1	7.891	0.256
MIL-C-5	CM	N_S	MIL	0	59.090	0.015
MIL-C-5	CM	S_F	Higher	0	0.665	1.376
MIL-C-5	CM	S_F	MIL	0	0.823	1.112
MIL-C-5	CM	N_S	Lower	0	111.500	0.0082
MIL-C-20	CC	G_F	Higher	0	4.063	0.225
MIL-C-20	CC	G_M	MIL	0	0.028	-
MIL-C-25	CP	A_{IT}	MIL	0	0.004	-
MIL-C-25	CP	G_F	MIL	0	195.673	0.0047
MIL-C-25	CP	G_M	MIL	4	1.147	4.577
MIL-C-25	CP	N_S	MIL	114	374.635	0.314
MIL-C-25	CP	S_F	MIL	0	0.392	-
MIL-C-62	CE	G_F	MIL	7	120.335	0.070
MIL-C-62	CE	G_M	MIL	0	0.167	-
MIL-C-62	CE	N_S	MIL	4	9.172	0.572
MIL-C-62	CE	N_S	Lower	1	10.500	0.192

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-2 (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS (x 10^6)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-C-81	CV	G_F	MIL	11	132.635	0.095
MIL-C-81	CV	G_M	MIL	0	0.083	-
MIL-C-81	CV	N_S	MIL	0	0.749	1.222
MIL-C-81	CV	S_F	Higher	0	120.444	0.0076
MIL-C-81	CV	S_F	MIL	0	140.009	0.0065
MIL-C-92	CT	G_F	MIL	13	70.197	0.208
MIL-C-92	CT	N_S	MIL	0	0.180	-
MIL-C-92	CT	S_F	Higher	0	0.055	-
MIL-C-92	CT	S_F	MIL	0	3.667	0.250
MIL-C-3965	CL	A_{IF}	MIL	29	9.193	3.378
MIL-C-3965	CL	A_{IT}	MIL	4	5.364	0.979
MIL-C-3965	CL	G_F	Higher	0	0.143	-
MIL-C-3965	CL	G_F	MIL	36	2746.820	0.014
MIL-C-3965	CL	G_M	MIL	13	39.755	0.367
MIL-C-3965	CL	N_S	MIL	344	9667.418	0.036
MIL-C-3965	CL	S_F	MIL	0	0.265	-
MIL-C-3965	CL	G_B	Higher	11	5104.420	0.0025

* All failure rates are calculated at upper single-sided 60 percent confidence level

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TABLE A-2 (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-C-10950	CB	G_F	MIL	0	4.198	0.218
MIL-C-10950	CB	N_U	MIL	1	5.262	0.384
MIL-C-10950	CB	S_F	MIL	0	0.170	-
MIL-C-10950	CB	N_S	MIL	0	2.369	0.386
MIL-C-11015	CK	A_{IF}	MIL	30	725.122	0.044
MIL-C-11015	CK	A_{IT}	MIL	4	201.724	0.026
MIL-C-11015	CK	G_F	MIL	22	6,121.487	0.0039
MIL-C-11015	CK	G_M	MIL	0	103.910	0.0088
MIL-C-11015	CK	N_S	MIL	16	4,211.996	0.0042
MIL-C-11015	CK	S_F	Higher	0	0.526	1.740
MIL-C-11272	CY	A_{IF}	MIL	4	18.273	0.287
MIL-C-11272	CY	A_{IT}	MIL	0	55.854	0.016
MIL-C-11272	CY	G_F	MIL	0	893.290	0.0010
MIL-C-11272	CY	G_M	MIL	0	5.764	0.159
MIL-C-11272	CY	N_S	MIL	33	13,241.321	0.0027
MIL-C-11272	CY	S_F	MIL	0	398.421	0.0023

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-2 (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($\times 10^6$)	FAILURE RATE* (FAIL./10^6)
MIL-C-11693	CZ	A_{IT}	MIL	3	0.771	5.415
MIL-C-11693	CZ	G_F	MIL	15	188.799	0.088
MIL-C-11693	CZ	S_F	Higher	0	0.164	-
MIL-C-11693	CZ	N_S	MIL	0	3.702	0.247
MIL-C-12889	CA	G_F	MIL	3	11.662	0.358
MIL-C-14157	CPV	A_{IF}	MIL	4	10.090	0.520
MIL-C-14157	CPV	G_F	M	0	15.602	0.059
MIL-C-14157	CPV	G_F	S	0	46.125	0.020
MIL-C-14157	CPV	S_F	P	0	0.079	-
MIL-C-14157	CPV	N_S	MIL	1	1007.790	0.0020
MIL-C-14409	PC	G_F	MIL	0	7.118	0.129
MIL-C-14409	PC	N_S	MIL	0	0.064	-
MIL-C-18312	CH	A_{IT}	MIL	0	1.248	0.733
MIL-C-18312	CH	G_M	MIL	0	0.118	-
MIL-C-18312	CH	N_S	MIL	1	33.754	0.060
MIL-C-19978	CQ	G_F	MIL	12	746.095	0.018
MIL-C-19978	CQ	G_M	MIL	0	0.181	-
MIL-C-19978	CQ	N_S	MIL	15	619.138	0.027

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-2 (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-C-19978	CQR	G_B	S	0	6.791	0.135
MIL-C-19978	CQR	S_F	P	0	0.014	-
MIL-C-23269	CYR	A_{IT}	L	0	0.001	-
MIL-C-23269	CYR	A_{UT}	M	0	0.008	-
MIL-C-23269	CYR	G_B	S	0	931.332	0.00098
MIL-C-23269	CYR	G_F	L	0	4.782	0.191
MIL-C-23269	CYR	G_M	M	0	0.487	-
MIL-C-23269	CYR	S_F	P	0	96.805	0.0095
MIL-C-23269	CYR	N_S	M	0	732.021	0.0012
MIL-C-26655	CS	A_{IF}	MIL	28	43.013	0.700
MIL-C-26655	CS	A_{IT}	MIL	17	198.039	0.095
MIL-C-26655	CS	G_F	MIL	35	1869.840	0.020
MIL-C-26655	CS	G_M	MIL	2	2.572	1.207
MIL-C-26655	CS	N_S	MIL	15	625.561	0.027
MIL-C-26655	CS	S_F	MIL	0	23.924	0.038
MIL-C-39001	CMR	A_{IT}	L	0	0.007	-
MIL-C-39001	CMR	A_{IT}	P	0	0.132	-
MIL-C-39001	CMR	G_M	P	0	0.375	-
MIL-C-39001	CMR	S_F	R	0	0.213	-

* All failure rates are calculated at upper single-sided 60 percent confidence level

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TABLE A-2 (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
MIL-C-39003	CSR	A_{IT}	M	2	385.729	0.0080
MIL-C-39003	CSR	A_{IT}	P	0	0.426	-
MIL-C-39003	CSR	A_{UT}	M	0	0.027	-
MIL-C-39003	CSR	A_{UT}	R	4	43.908	0.120
MIL-C-39003	CSR	G_B	S	0	8561.100	0.00011
MIL-C-39003	CSR	G_F	L	2	85.684	0.036
MIL-C-39003	CSR	G_F	M	4	174.362	0.030
MIL-C-39003	CSR	G_F	P	0	2.075	0.441
MIL-C-39003	CSR	G_F	R	0	0.069	-
MIL-C-39003	CSR	G_F	S	1	33.415	0.060
MIL-C-39003	CSR	G_M	M	2	16.961	0.183
MIL-C-39003	CSR	N_S	M	0	37.169	0.025
MIL-C-39003	CSR	N_S	P	0	0.939	0.974
MIL-C-39003	CSR	N_S	R	0	0.030	-
MIL-C-39003	CSR	N_S	S	0	2984.940	0.00031
MIL-C-39003	CSR	S_F	P	1	370.749	0.0054
MIL-C-39003	CSR	S_F	S	0	9.692	0.094

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-2 (Cont)

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PART TYPE						FAILURE RATE* (FAIL./10^6 HRS)
MIL-C-39006	CLR	A_{IT}	P	0	0.079	-
MIL-C-39006	CLR	A_{UT}	M	0	0.001	-
MIL-C-39006	CLR	G_B	S	1	1094.040	0.0018
MIL-C-39006	CLR	G_F	M	0	0.096	-
MIL-C-39006	CLR	G_M	M	0	0.066	-
MIL-C-39006	CLR	N_S	M	0	0.039	-
MIL-C-39006	CLR	N_S	P	0	104.236	0.0088
MIL-C-39006	CLR	S_F	P	0	76.429	0.012
MIL-C-39014	CKR	A_{IT}	L	0	0.048	-
MIL-C-39014	CKR	A_{IT}	P	0	2.402	0.381
MIL-C-39014	CKR	A_{UT}	M	0	0.053	-
MIL-C-39014	CKR	A_{UT}	R	0	42.864	0.021
MIL-C-39014	CKR	G_B	S	3	17,638.800	0.00024
MIL-C-39014	CKR	G_F	M	0	20.542	0.045
MIL-C-39014	CKR	G_F	P	0	0.510	1.794
MIL-C-39014	CKR	G_F	R	0	2.465	0.371
MIL-C-39014	CKR	G_F	S	0	0.528	1.733
MIL-C-39014	CKR	G_M	L	0	0.153	-
MIL-C-39014	CKR	G_M	P	0	8.247	0.111
MIL-C-39014	CKR	N_S	M	0	10.761	0.085

* All failure rates are calculated at upper single-sided 60 percent confidence level

TABLE A-2 (Cont)

PART TYPE		ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x 10^6$)	FAILURE RATE* ($FAIL./10^6$ HRS)
MIL-C-39014	CKR	N_S	P	0	0.222	-
MIL-C-39014	CKR	N_S	R	0	1.024	0.894
MIL-C-39014	CKR	N_S	S	0	170.784	0.0054
MIL-C-39014	CKR	S_F	P	0	549.172	0.0017
MIL-C-39014	CKR	S_F	R	0	117.192	0.0078
MIL-C-39018	CU	A_{IT}	Higher	3	89.894	0.046
MIL-C-39018	CU	A_{IT}	MIL	0	0.020	-
MIL-C-39018	CU	G_B	MIL	0	4.527	0.202
MIL-C-39018	CU	G_F	MIL	0	0.175	-
MIL-C-39018	CU	G_M	MIL	0	0.444	-
MIL-C-39018	CU	N_S	MIL	0	0.122	-
MIL-C-39022	CHR	G_M	M	0	0.177	-
MIL-C-39022	CHR	S_F	P	0	1.600	0.572
MIL-C-39022	CHR	N_S	M	0	198.996	0.0046
MIL-C-83421	CRH	G_F	M	0	1.024	0.894
MIL-C-83421	CRH	G_M	M	0	0.014	-
MIL-C-83421	CRH	N_S	M	0	0.427	-
TOTALS				890	87,192.848	

TABLE A-3

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Transformer Operating Data Summary

[illegible]			[illegible]	PART HOURS ($x\ 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
AUDIO	G_F	MIL	10	174.503	0.066
AUDIO	N_S	MIL	47	240.304	0.206
POWER	G_F	MIL	6	43.529	0.169
POWER	N_S	MIL	2	122.642	0.025
POWER	G_M	MIL	2	2.157	1.440
POWER	A_I	MIL	3	1.244	3.410
POWER	G_B	LOWER	16	0.875	20.200
POWER	G_M	LOWER	0	0.084	-
PULSE	G_F	MIL	2	501.983	0.006
PULSE	N_S	MIL	9	184.803	0.057
PULSE	A_I	MIL	3	6.488	0.643
PULSE	G_M	MIL	1	0.227	8.900
PULSE	G_M	LOWER	0	0.915	1.000
RF	G_F	MIL	10	36.540	0.315
RF	S_F	MIL	0	83.587	0.011
TOTALS			111	1399.881	

* [illegible] 60 percent confidence level

TABLE A-4

RF Coil Operating Data Summary

PART TYPE	ENVIRONMENT	QUALITY	FAILURES	PART HOURS ($x 10^6$)	FAILURE RATE* (FAIL./10^6 HRS)
GENERAL	G_F	MIL	9	2174.147	0.005
GENERAL	N_S	MIL	6	595.053	0.012
GENERAL	S_F	MIL	0	287.091	0.003
GENERAL	A_I	MIL	1	2.188	0.923
GENERAL	G_M	MIL	0	0.718	1.274
TOTAL			16	3059.197	

* All failure rates are calculated at upper single-sided 60 percent confidence level

APPENDIX B

LIST OF DATA SOURCES

1. Aerojet Electro Systems Company
   Azusa, California

2. E-Systems Inc.
   ECI Division
   St. Petersburg, Florida

3. E-Systems Inc.
   Melpar Division
   Falls Church, Virginia

4. Ford Aerospace and Communications Corporation
   Palo Alto, California

5. General Dynamics
   Electronics Division
   San Diego, California

6. General Dynamics
   Pomona, California

7. General Electric Company
   Syracuse, New York

8. GIDEP Operations Center
   Corona, California

9. Harris Corporation
   Melbourne, Florida

10. Lear Siegler Inc.
    Instrument Division
    Grand Rapids, Michigan

11. Litton Data Systems
    Van Nuys, California

12. Magnavox Company
    Fort Wayne, Indiana

13. Martin Marietta Corporation
    Orlando Division
    Orlando, Florida

14. Raytheon Company
    Equipment Division
    Wayland, Massachusetts

15. RCA
Consumer Products Division
Indianapolis, Indiana

16. Rockwell International
Autonetics Division
Anaheim, California

17. Sperry Systems Management
Great Neck, New York

18. Sperry Univac
Defense Systems Division
Minneapolis, Minnesota

19. Tektronix, Inc.
Beaverton, Oregon